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Soy biodiesel pathways: Global prospects

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ABSTRACT

This survey paper critically reviews the performance and prospects of soy biodiesel production on a global basis as assessed by some 30 life-cycle analyses (LCAs). The paper compares agricultural and industrial practices. Soy biodiesel is not a most sustainable product in all global circumstances. Life-cycle energy depends on specific climatic conditions, and on the agro- and processing technologies used. Alternative oilcrop cultivation practices and technologies were evaluated. Opportunities have been identified to improve the biodiesel life-cycle energy efficiency and environmental impact in relevant production areas (mainly USA, Brazil, Argentina and P.R. China) by implementing new technologies in agriculture as well as in industrial processing. The consequences of large-scale renewable energy action plans in the European Union and of biodiesel mandates in numerous countries worldwide are critically considered. The paper concludes with perspectives and recommendations.

Contents

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1. Introduction

Liquid biofuels (107.5 billion L) provided about 3% of global road transport fuels in 2011. Amongst these, biodiesel (20%) is the dominant product in Europe and Asia and bioethanol (80%) in the Americas. The potential volumes of these biofuels are limited. As the land area requirements for biodiesel production are considerably larger than for bioethanol, it is unlikely that biodiesel will ever reach the same production level as bioethanol. Moreover, there exist serious concerns regarding interferences of biofuels with food supplies [1], as expressed by organisations such as OECD-FAO [2], IMF, World Bank and Oxfam, as well as reported poor energy balances, ecosystem destruction and land displacement issues [3,4]. More advanced biofuels without most of the environmental drawbacks of first-generation biofuels are still immature with little prospectives of significant market penetration before 2020.

The term 'biodiesel' (BD) was coined by Wang [5] in 1988. There is huge interest in biodiesel. SciFinder 2011 reports 1766 articles and 679 patents related to biodiesel 2010. Perceived benefits of biodiesel (fatty acid methyl esters, FAMEs) are many: political (national energy security); economical (trade balance, employment); agricultural (rural development); environmental (renewable, biodegradable/non-ecotoxic, emissions savings); technical (engine lubricity); health (less harmful exhaust emissions); and safety (higher flash points). Vegetable oil esters are much more biodegradable ($>95\%$) than mineral oils (25–40%) and consequently pollute less than conventional diesel (CD) in a sector (transportation) which is an important contributor to global greenhouse gas (GHG) emissions [6]. Biodiesel's suitability as a fuel is determined by its ignition quality (cetane number, CN), heat of combustion, pour point (PP), cloud point (CP) and (kinematic) viscosity [7]. Biodiesel is miscible with conventional diesel in all ratios and can be used in diesel engines without significant engine modifications. Some problems connected with biodiesel use are oxidative (in)stability, cold-flow properties, slightly enhanced NO_X exhaust emissions [8], and price. The product needs further improvement both ecologically and economically.

Biodiesel was originally conceived largely in the context of national fuel needs [9] and use of local resources but has emerged more recently as a global industry and commodity. Biodiesel production (2010) worldwide amounted to about 16.1 Mt (Europe 9.5 Mt, USA 1.1 Mt, Argentina and Brazil 3.8 Mt, ROW 1.7 Mt), which was mainly derived from rapeseed oil (47%), soybean oil (35%), palm oil (10%), sunflower oil (4%) and other oils and fats (including tallow, waste oils and corn oil) (4%). International biodiesel trade streams were of the order of 2.25 Mt in 2010 [10].

At variance to soybeans and associated products (meal, oil), which are driven by global market forces, biodiesel production does not depend on such free market forces but is merely determined by political choices and governmental incentives such as mandates, subsidies and tax cuts, at both sides of the Atlantic. Mandates pass the higher costs directly to the consumer; subsidies are transfers from governments to industry. In May 2003, the European Union (EU) has issued the Biofuels Directive (2003/30/EC) with a specific EU-wide obligation of 5.75% (by energy) or about 18.0 Mt/yr of biofuels for the transport sector by 2010. Although this target was not even met in an unsustainable way by most member states (actual average blending of only 4.26%), a still more ambitious EU biofuels target of 10% (by energy for 2020) has later been defined in the Renewable Energy Directive 2009/28/EC (RED) [11]. This target is not unchallenged (as voiced by many). A regulations rethink is necessary. Global biofuels policy issues are increasingly leading to undesired consequences. Expanded oilseed production is limited by the availability of cropland. Indiscriminately increasing the amount of biofuels may not automatically lead to the best reductions in emissions [12]. In particular, indirect land-use changes are a valid concern.

Biodiesel has been a fast growing alternative fuel in Europe (from 300 kt in 1998 to 10.6 Mt in 2011) as well as in the United States (from 2 Mg in 2000 to over 800 Mg in 2011). EPA has extended its Renewable Fuel Standard (RFS2) volumetric compliance level from 500 Mgal/yr in 2009 to 1 Bgal/yr by 2012. It is to be noticed that domestic US diesel use is very limited, quite opposed to the consumption in Europe. Expectations of entrepreneurs have run high and as a result biodiesel nameplate capacity has grown abnormally and beyond measure (up to 22.1 Mt/yr in Europe 2011; 3.0 Bg in USA) and currently determines largely underutilised EU and US capacities and idle plants, undermining the economics of the biodiesel sector as a whole. Worldwide use of the niche product biodiesel stays marginal and just accounts for 4.5% of diesel use in Europe and 1.7% in the USA.

Greenhouse gas emissions must be reduced by 50% to 85% by 2050 if global warming is to be confined to between 2 °C and 2.4 °C [13]. Transport is the only sector that has seen its emissions increase over the past two decades. An OECD recommendation [2] urges replacing mandates for biofuels production by technologically neutral policies (such as carbon taxes) that stimulate energy efficiency and by a certification requirement. The EU's Fuel Quality Directive (FQD) aims at reducing transport fuel emissions by 6% by 2020 [14]. Because the carbon in biodiesel is recycled, the product is advocated as a partial solution to the increasing atmospheric CO_2 concentrations [15]. However, there is little consensus on the degree of sustainability for various agricultural cultivation practices and production methods. Clearly, the total emission of all GHGs required to produce, transport, and process the biodiesel feedstock must be less than the emissions from the displaced fossil fuel. As illustrated for the case of rape biodiesel [16], a range of such products exists differing widely in terms of energy balance, environmental sustainability as well as in economic profitability.

The net benefits of biodiesel production from energetic, environmental, and socio-economic perspectives are still widely debated [3,4,12,17–20]. Although certain conditions are inductive to a negative energy balance for biodiesel [21,22], most others have determined net positive balances. These situations generally rely on modern agricultural production technologies, resulting in higher yields and lower energy inputs in crop production (*e.g.* more efficient fertiliser management, reduced tillage).

As the use of bioenergy crops has recently come under serious criticism as to their true environmental cost [23,24] it is an objective of this survey paper to gain insight into the future prospects of soy biodiesel in a global energy system. Quantification of the net impacts of various widely available soybean oil feedstocks by life-cycle assessments (LCAs) from field to fuel use provides a way of determining the relative benefits of respective production pathways and of biodiesel in comparison with fossil diesel [25]. In this paper we have compared a set of very recent LCAs of soy biodiesel (*cf.* Table 1). The conclusions from these studies differ significantly. Data on soybean production methods and agricultural practices are georeferenced.

This paper critically analyses soybean-based biodiesel production worldwide but focuses more in particular on the four main producers (USA, Brazil, Argentina and China). Developing countries such as Brazil and Argentina have favourable climatic and environmental conditions for plant growth, low labour costs, low energy input in agricultural production and hence low production costs for energy crops. The limit to growth and spread of soybeans is the capacity of global markets to absorb additional sustainable production. The potential of soy biodiesel is constrained by the growing demand of edible oil and by its sustainability.

Other objectives of this paper are the identification of the most important environmental loads in soy biodiesel life-cycle systems

Table 1
Recent life-cycle assessments of soybean biodiesel pathways.

Feed	LCA framework	Functional unit	Application	Location	Tools	Methods	Impact categories	Year	Reference(s)
Soybean	WTI	1 kg of soybeans exported to Europe	Soybean production	Latin America	–	–	GHG, LUC	2011	[63]
Soybean	WTP	Energy consumed per litre of biodiesel produced	Comparison between three studies	USA	GREET	–	FER	2011	[50]
Soybean, rapeseed, sunflower	WTP	1 kg of biodiesel produced	Biodiesel production	(Spain?)	–	Eco-Indicator 99	EQ, HH, RD	2011	[77]
Soybean, jatropha, microalgae	WTW	1 MJ of energy production	Environmental impacts by biodiesel production and transport powered with biodiesel	China	Gabi 4.3	CML 2001	ADP, AP, EP, FAETP, GWP, HTP, ODP, MAETP, POCP, TETP	2010	[78]
Soybean	WTP	1 L of biodiesel	Biodiesel production	Brazil	–	EA, EEA, MFA	–	2010	[79,80]
Soybean	WTW	1 MJ of combustion energy	Combustion of biodiesel and LPG in diesel engines	Portugal	–	Eco-Indicator 99, EPS 2000	ADP, AP, EP, FAETP, GWP, HTP, LUC, MAETP, ODP, POCP, TE, TETP	2010	[62]
Soybean	WTW	1 t of output	Production of soybean and soy industrial products	USA	SimaPro 7, ecoinvent	–	AP, CAP, CE, EP, ET, FFD, GWP, HH, ODP, PS, TFE, WF	2010	[46]
Soybean	WTW	1 million Btu of fuel produced and used	Combustion of biodiesel, renewable diesel and gasoline	USA	GREET, ecoinvent 2.01	–	FEC, PEC, TEC	2009	[47]
Soybean	WTE, WTW	1 km driven with B100 by a 28 t truck	Combustion of biodiesel and diesel in diesel engines	Argentina, Switzerland	ecoinvent 2.01	–	AETP, AP, CED, EP, GWP, HTP, LUC, TETP	2009	[38]
Soybean, jatropha, used cooking oil	WTW	1 MJ of combustion energy	Biodiesel and biofuel production	China	GREET	–	FEC, GWP	2009	[21]
Soybean	WTP	1 t biodiesel produced	Biodiesel production	Argentina	GREET v1.8	–	EBR	2009	[40]
Soybean	WTW	1 MJ of combustion energy	Biodiesel production	USA	–	–	GWP	2009	[52]
Soybean	WTP	Energy consumed per litre of biodiesel produced	Comparison between three studies	USA	GREET		EIQ, FER	2009	[37]
Soybean	WTE	1 kg of soybean meal	Soymeal production	Argentina	SimaPro 6	EDIP 97 v 2.3	AP, EP, GWP, ODP, PS	2008	[41]
Soybean	WTW	1000 L of biodiesel produced	Biodiesel production and utilisation	USA	GREET v1.8	–	EB, GWP	2008	[44]
Soybean	WTP	Drive 100 km with an identical car in the same conditions	Comparison between biodiesel and diesel powered car	China	GREET	–	EAP, FEC, GHG, PM, TEC	2008	[49]
Soybean, rapeseed	WTP	1 kg of biodiesel produced	Biodiesel production on deforested land	Brazil, Europe	–	–	GWP, LUC	2008	[4]
Soybean	WTP	Energy consumed per litre of biodiesel produced	Biodiesel production	Argentina	–	–	EB, GWP	2008	[39,81]
Soybean, rapeseed, palm, used cooking oil, bioethanol, biogas	WTW	1 MJ of energy	Combustion	Brazil, USA, Switzerland	ecoinvent 1.3	Eco-Indicator 99, UBP 06	CED, GHG, GWP	2007	[82]
Soybean	CTF	1 kg dry harvested matter	Comparison of farming methods	Switzerland	ecoinvent 1.2	EDIP 97, SALCA	AETP, AP, EB, EP, GHG, HTP, ODP, TETP	2007	[83]
Soybean	CTF	1 kg crop	Oilcrop production	USA	GREET 1.6	–	EB, GHG	2007	[48]
Soybean, corn, alfalfa	WTW	1 m^2 oilcrop	Crop production	Pennsylvania	–	DAYCENT	CED, GWP	2007	[43]
Soybean, canola	WTP	Biodiesel produced from 1.0 t of soybean or canola	Biodiesel production	Canada	–	–	EBR	2007	[42]
Soybean, corn	WTW	1 MJ of energy production	Biofuels production	USA	–	–	EBR, GHG	2006	[20]
Soybean, sunflower	WTW	1 t of biodiesel	Biodiesel production	USA	–	–	EBR	2005	[84]
Soybean, corn	WTW	1 ha of arable land	Biodiesel production	USA	TRACI	–	AP, CED, EP, GWP	2005	[58]

Table 1 (*continued*)

Feed	LCA framework	Functional unit	Application	Location	Tools	Methods	Impact categories	Year	Reference(s)
Soybean, corn, alfalfa switchgrass	CTF	1 kg of biomass crop production	Crop production	USA	GREET 1.5a	–	CER, GWP	2004	[85]
Soybean, rapeseed, sunflower	–	1 ha oilcrop	Oilseed biodiesel production	Europe	–	–	EBR	2003	[22]
Soybean, canola, tallow, used cooking oil	WTW	Biodiesel produced from 1.0 t of soybeans	Biodiesel production	Australia	SimaPro	–	EB, GHG, PM	2002	[53]
Soybean, palm oil, rapeseed	CTF	1 ha oilcrop	Oilseed production	Brazil, Malaysia, Sweden	–	–	LU	2000	[66]
Soybean	WTW	1 brake-horsepower-hour (bhp-h)	Urban bus powered with (bio)diesel	USA	TEAM	–	CED, EAP, EB, EWE, FSW, GWP	1998	[29]

CFT, cradle-to-farm gate; WTE, well-to-exportation port; WTI well-to-importation port; WTP, well-to-pump; WTW, well-to-wheels.
ADP, abiotic depletion potential; AETP, aquatic ecotoxicity potential; AP, acidification potential; BD, biodiversity; CAP, criteria air pollutants; CE, carcinogenic effects; CED, non-renewable energy consumption; CER, cumulative energy requirement; EA, emergy accounting; EAP, emission of air pollutants; EB(R) energy balance ratio; EEA, embodied energy analysis; EP, (aquatic) eutrophication potential; EQ, ecosystem quality; EROI, energy return on investment; ET, ecotoxicity; EWE, emission water effluents; FAETP, fresh water aquatic ecotoxicity potential; FEC, fossil energy consumption; FER, fossil energy ratio; FFD, fossil fuel depletion; FSW, flow of solid waste; GHG, greenhouse gas; GWP, global warming potential; HH human health; HTP, human toxicity potential; LU, land-use competition; LUC, land-use change; MAETP, marine aquatic ecotoxicity potential; MFA, material flow accounting; NER, net energy ratio; NP, nutrification potential; NRW, non radioactive waste; ODP, ozone layer depletion; ORE, organic respiratory effects; PEC, petroleum energy consumption; PM, particulate matter; POCP photochemical potential; PS, photo smog; RAD, radioactive radiation; RD, resource depletion; RW, radioactive waste; TE, terrestrial eutrophication; TEC, total energy consumption; TETP, terrestrial ecotoxicity potential; TFE, total fuel energy; WF, water footprint.

and making suggestions for substantial improvement. Because of regional specificities, the environmental performance of soy biodiesel pathways in the main producing areas can be expected to differ considerably. Current practice shows considerable bandwidths of the potentials, environmental impacts and costs of soy biodiesel. Best practices are identified and can be used to improve performance of laggards in agricultural and manufacturing processes.

2. Biodiesel life cycle

The biodiesel life cycle consists of an agricultural stage, including oil milling, oil extraction/refining, and transportation. The industrial stage comprises pretreatment, vegetable oil (trans)esterification and biodiesel transport to the fuel pump. The fuel stage consists in combustion. A biodiesel pathway thus involves three economic sectors, namely agriculture, industry and services (Fig. 1).

Although biodiesel might be considered as a more environmentally friendly product than petrodiesel, production of agricultural raw materials is connected with various impacts that do not occur in case of fossil fuels (*e.g.* fertilisers, pesticides, water footprint, contamination of ground and surface water). A full LCA of biodiesel from biomass production *via* conversion to end use as an energy source is then required in order to obtain better insight. Production of biodiesel generally needs non-renewable energy such as fossil fuel required for machinery in the agricultural and industrial phase, for transportation of raw materials, inputs and distribution of biofuel for final use, and embedded energy in chemicals (fertilisers, agrochemicals, methanol). Also biomass processing (crushing, extraction) requires considerable amounts of fossil fuels. Production and use of biodiesel entails emissions to the environment (air, water and soil) coming mainly from the application of fertilisers in the agricultural phase, emissions from fuel combustion and solvents during industrial operations (transportation, oil extraction, transesterification), and use (combustion). Climatological factors (type of soil, weather) strongly influence the environmental impacts. Past land use, by-product formation and the technological process path are all factors to be considered. Thus it makes sense to examine in detail LCAs of soy biodiesel of various origins.

The conversion of vegetable oil to biodiesel typically involves the steps of vegetable oil extraction, feedstock pretreatment, transesterification, alcohol recycling, and crude alkyl ester purification. In the crushing facility beans are dried to a moisture level of 10.5%, which is optimal for storage and crushing. Drying is a highly energy intensive process. Oil is extracted from cleaned seeds (with global average yield of 15.6%). The hexane extraction method is most commonly used in large-scale soybean seed crushing. Oil extraction by solvents is less economical than mechanical separation since the desolventising and distillation processes to separate the solvent from the meal and the oil to recirculate the solvent is an energy (steam) consuming process. Crude vegetable oil is post-treated with processes of deacidification, degumming and drying to remove residual free fatty acids (FFAs), phospholipids and water. For details on the separation of the soybean into oil and soybean meal (crushing) and further processing (degumming, deodorisation, bleaching and neutralisation), *cf.* Ref. [26]. New oil recovery processes are being developed [27].

Biodiesel is produced through transesterification of crude or refined vegetable oil and (usually) methanol in the conditions of catalysis (usually alkaline), heating and pressurising. Excessive methanol is recycled. Crude methyl ester is treated by washing, fractionation and drying to obtain biodiesel end-products. The transesterification process requires steam and electricity as energy inputs and produces both biodiesel and glycerin. Biodiesel and glycerin are reportedly produced in weight ratios of 1:0.116 [28] to

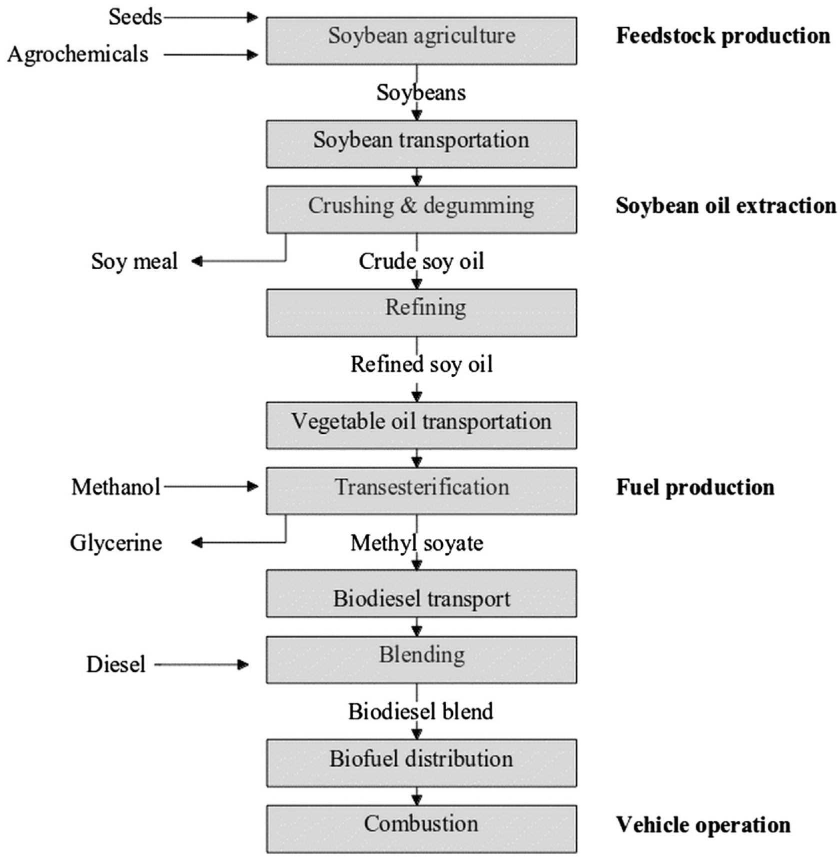

Fig. 1. Unit processes in the well-to-wheels life-cycle for soybean-based biodiesel.

1:0.213 [29]; GREET value 0.213. A product yield ratio (wt/wt) of 1:0.104 is more realistic for soy biodiesel [30].

Enzymatic synthesis of biodiesel by various lipase catalysts has received much attention due to the lower energy requirements and selectivity of the catalyst [31]. Even though conversion rates are generally slower in the enzyme catalysed route, interest in the process is justified by the resultant simplifications and lower reaction temperatures. Advances in technology have also resulted in lower catalyst costs [32]. Lipase catalysts do not impose restrictions on the water content or level of free fatty acids in the oil, and are able to yield similar conversions to the alkali catalyst route. Ester yield is high and no saponification occurs. Although enzymatic processes offer perhaps great potential for future production, the relatively slow rate of enzymatic reactions and the (still) high cost of enzymes have made the enzymatic processes economically unfavourable. There are as yet no industrial-scale processes for biodiesel based on enzymatic transesterification.

The whole life cycle puts into a clearer perspective the advantages in terms of reduction of greenhouse effect and national fossil energy dependency. In order to comply with modern sustainability criteria biodiesel producers need to evaluate the environmental and energetical performances of their product. As shown below (*cf.* Table 22), the EU default value for life-cycle GHG emission savings for soy biodiesel (mainly imported) does not comply with the legal minimum value (35%), at variance to the mainly domestic rape biodiesel. This puts soy biodiesel on a disadvantage in the European market. In addition to energy yield, carbon budget and economic cost, proper evaluation of a product should take into account many different social and environmental factors. Many studies have appeared that evaluate one or more of these aspects of biodiesel production, but only few make an attempt to present a more comprehensive evaluation [33,34]. In conjunction with other measurements such as environmental and economic terms renewability is a useful consideration to assess biodiesel benefits.

3. Life-cycle assessment of biodiesel

Life-cycle assessment according to the ISO standards 14040 (2006) and 14044 (2006) evaluates potential inputs (in terms of energy, environmental burdens) throughout the life cycle of a product, process or activity from extraction of raw materials through production and use, to final disposal. LCA is largely a site-generic assessment tool, *i.e.* not location or time-specific. Life-cycle assessment has become an important decision-making tool for promoting alternative fuels and is indispensable to consolidate product credibility on the international market. An LCA approach is data intensive; there is a general lack of local data in developing countries. Despite standardisation LCA methodology varies widely making simple direct comparison extremely difficult.

Rapid expansion in demand for biodiesel has raised concerns that feedstock production is causing both direct and indirect negative effects, such as water supply concerns, local environmental impacts on air, water and soil quality, habitat destruction and social issues (working conditions). LCA is not a measure of the value society places on a product and social sustainability is not considered [35]

Some limitations of the environmental LCA method are determined by the definition of system boundaries, allocation of impacts and temporal resolution. Most LCAs overlook soil carbon emissions from changes in land use and hence they only provide a partial analysis in the sense that they only count the carbon benefits of using land for biodiesel crops and thus do not include other factors such as carbon costs, carbon storage and sequestration sacrificed by diverting land from its existing use [3]. Even in the absence of land-use change

emissions different LCA studies disagree on the GHG balance of a variety of biodiesel cropping systems (*cf.* Section 5.2.2). To further complicate matters, GHG calculation methodologies differ for EU RED [11] and US EPA [36]. The GHG or carbon costs are very dependent on what the bioenergy crop might be replacing. In the vehicle use phase direct assessment of engine exhaust emissions is possible [8].

3.1. Life-cycle boundaries

LCA sets appropriate boundaries (process stages, geographical coverage, time-frame, scale) and defines the reference systems used for comparison and the allocation of the environmental burdens among co-products. A comparison between results is often impractical and prone to misinterpretation when boundaries and other assumptions differ considerably.

The conventional diesel life cycle starts at crude oil extraction and ends at CD combustion, as shown in Fig. 1. A Well-to-Tank (WTT) evaluation accounts for the energy expended and the associated GHG emitted in the steps required to deliver the finished fuel into the on-board tank of a vehicle. The Tank-to-Wheels (TTW) evaluation accounts for the energy expended and the GHG emitted by the vehicle/fuel combination. The Well-to-Wheels approach combines WTT and TTW.

Life-cycle assessment of biodiesel production requires a regional-specific approach (geographical reference). Agricultural conditions (soil type; temperate or tropical; weather conditions) and practices (*e.g.* tilling, fertilisation), feedstocks (various oilseeds), crop yields, land use (marginal and set-aside land), energy sources (electricity, coal, nuclear) and transport distances can vary significantly from one region to another as well as in time (determined by agricultural and technological advances). Consequently, LCA studies for specific locations may not be applied automatically to other regions. LCAs are only valid for a given time-frame as technologies, production methods and market values are subject to change in the medium term. Business models evaluated comprise both integrated oil mill–biodiesel plants [37–39] and stand-alone crusher and transesterification units at different locations [29]. The former model is typical for Argentina. The effects of plant scale have been evaluated and range from small- and medium-sized plants [37] to large-scale biodiesel units [40]. Also the feasibility of production of biodiesel as a commodity has been considered [12,18], *cf.* also Section 5.3. Clearly, comparison of the energy consumption and GHG emissions of biodiesel pathways in various conditions is useful to develop strategies and policies promoting large-scale development of the biodiesel industry at the most advanced level.

3.2. Life-cycle inventory allocation

During the biodiesel life cycle so-called coupled products are co-generated, such as straw and oilcake, and crude glycerol from the production of soy methyl ester (SME). When comparing SME (soy biodiesel) with the substitute fossil energy source, these co-products provide an additional usefulness, which must carefully be accounted for. Allocation is necessary in multi-output processes, as in case of biodiesel LCAs. Approaches used include displacement and more or less arbitrary allocations in terms of mass- or volume-based partitioning, energy value, or economic revenue (market value). With the displacement method, 100% of the energy and emission burdens are attributed to the primary product (soymeal!) and a conventional product is assumed to be displaced by the co-product.

In analysing farm-based processes economic, energy and weight allocations are the norm even though ISO 14048:2006 gives preference to the "system boundary expansion" analysis method. In the substitution method, the system is expanded with avoided processes to remove additional functions related to the functional flows. However, there are situations in which no substitution effects can be ascertained. For example, glycerine produced during transesterification of vegetable oil cannot substitute glycerine in soap production, because soap is produced completely independently of the glycerine market. Soy biodiesel is a difficult pathway to treat using the substitution methodology because of the high proportion of soymeal (80 wt%) as a co-product [41–43]. The substitution method is appropriate for the purposes of policy analysis.

Allocation approaches are less data intensive and less challenging than displacement. However, various allocation approaches generate quite different results [20,38,41,44–47]. Comparisons of LCAs based on different allocation modes are not recommended. Neither mass allocation [37,41,46,48–51] nor energy allocation [20,44,52] is ideal for biodiesel systems because they do not recognise the nutritional differences between the oilseed meals. Since all of these meals are used almost exclusively for animal feed, valuing them on the basis of their mass or thermal energy contents is not appropriate. Physical allocation, based on well-defined inputs, invariable in time, is also recommended before economic allocation in ISO 14041. Allocation on price basis has been applied in several soy biodiesel LCAs [4,41,46,50,51,53]. For soybean milling, the economic allocation factors are approximately 36% for oil and 64% for meal. Economic allocation factors vary with relative world market prices (soybean meal and soy oil average prices of US$ 495.30/t and 1176.93/t respectively, March–September 2012).

Allocation on the basis of energy inputs is inappropriate as only biodiesel (and eventually straw) will actually be consumed in combustion for its energy content. An energy value-based allocation method is the best choice for systems in which the value of all products can be determined on the basis of their energy content, such as the production processes of renewable fuels [11]. Moreover, allocation of the energy inputs to the by-products (*e.g.* Refs. [20,44,52]) may be the correct procedure on a small scale, where the by-products can replace other similar products, but does not necessarily apply on a very large scale. This already holds for the glycerol glut, but also for meal in case of mega-scale biodiesel production as a consequence of national or regional renewable energy plans (*cf.* Section 5.3).

Another method of energy allocation is based on the replacement value of the primary product [54]. For biodiesel, the replacement value is based on the energy required to produce a substitute for each co-product. Although this is a preferred method [55] it is difficult to find an exact substitute for soybean meal. For instance, dried distillers grain (DDG) or rapeseed (canola) meals are animal feed products similar to soybean meal, but not substitutes with equal protein contents. Even if they were exact substitutes, it might be difficult to determine a precise replacement energy value. Using a system expansion approach, the soybean energy allocation is typically 63.3% for oil and 36.7% meal and that for canola is 88.1% for oil and 11.9% for meal, but these values vary slightly depending on tillage practices [42].

It is now generally accepted that the preferable method of determining co-product credits, which avoids allocation, would be to perform a system expansion [55–57]. This is endorsed by ISO 14041. Dalgaard et al. [41] used the method for the evaluation of the environmental consequences of soybean meal consumption. The procedure has also been applied in the life-cycle analysis of soybean cropping systems [58] and of soy biodiesel [42]. For allocation to crops in a cropping plan, *cf.* Ref. [59].

Biodiesel production systems generate various co-products and, depending on the approach used to allocate the emissions and impacts between biodiesel and co-products, the LCA results may vary significantly [60]. Many life-cycle analyses have neglected the

implications of modelling assumptions and data uncertainty assessment. A sensitivity analysis is required when several allocation approaches seem applicable [20,38,44,47].

3.3. Life-cycle impact assessment (LCIA)

Life-cycle results are always presented relative to a baseline system, *i.c.* petroleum diesel fuel. The fuel life cycle evaluates both direct energy consumption (petroleum products, electricity) and indirect energy consumption (used for production of materials and equipment). The energy balance stands for the energy consumed per unit of energy delivered. For biofuels, both the total energy balance and the fossil energy balance are relevant. The fossil energy ratio (FER) and net energy ratio (NER) are frequently used and have been defined as follows [50] (though not always in a consistent way [51]):

$$\text{FER} = \text{Renewable fuel energy output/Biodiesel share of fossil input} \tag{1}$$

$$\text{NER} = \text{Renewable fuel energy output/Biodiesel share of total energy input.} \tag{2}$$

The net energy ratio (NER) measures system efficiency. The biodiesel energy ratio (ratio of fuel energy to the total energy needed for biodiesel production) depends on climatic conditions and on the efficiency of the agro- and oil-processing technologies used. Straw has a large impact on the energy ratio. Usage of oilseed cake substantially improves energy conversion values, while the effect of glycerol is less. The impact of the transportation and utilisation phase depends on the transport distance and type of vehicle. Renewability requires a positive energy balance (EROI $>$ 1). However, not all forms of energy are equal. Technological advances in farming, oilcrop processing, and biodiesel conversion affect the life-cycle energy use over time, thus requiring LCA updates.

LCA answers the question whether biodiesel is environmentally friendlier than fossil diesel, with focus on global warming. Carbon emissions can be minimised throughout the biodiesel production process by application of sound science and engineering, agricultural best practice, maximising the use of biomass co-products (*i.c.* meal and glycerin) and by minimising transportation. In general, existing LCIA methods are associated with considerable uncertainties regarding toxicity. Most of the contributing impacts originate from pesticides (such as glyphosate) and heavy metals from fertilisers. Balances for the impact categories human toxicity and ecotoxicity are difficult to evaluate in view of insufficient databases in the area of fuel combustion. Land use and biodiversity are normally not well covered in LCA studies.

It is mostly the aim in LCA to present aggregated results. For the impact category land use, the information is a mix of quantitative and qualitative information. Consequently, land-use assessment is more descriptive and closer to environmental impact assessment (EIA). The land-use metric (GJ/ha/yr) provides insight into the strategic use of land and is most meaningful for the same land class. Land use covers a variety of aspects which must be included in LCA in different ways: area occupancy, land degradation and transformation, impact on biodiversity and aesthetic impact [61,62]. Attention should be given to the land area used as well as to making an assessment of the quality and sustainability of land use. As no impact assessment methods are available land use is seldom being taken into account in LCAs. Land-use changes were considered explicitly in Refs. [4,38,63–65]. Mattsson et al. [66] have formulated various impact sub-categories under the land-use category.

Direct land-use effects can be accounted for in LCA as changes in soil carbon and/or living biomass, between current land-use and that expected under biofuels. Indirect effects caused by the displacement of the original land-use are often not accounted for due to the difficulty of defining indirect effects. The difficulties with quantifying indirect GHG emissions were highlighted by Rowe et al. [25]. Currently, indirect effects are not clearly defined and cannot be accounted for in regional LCAs.

Crop displacement is another blind spot in agricultural LCAs. Increased agricultural production by increased cultivated area has land-use effects, whilst increased yields may have more pronounced effects relating to global warming and eutrophication. Methodology to evaluate land-use change is under development [67]. As land constraints and GHG emissions are a primary concern for EU-27 emissions savings per unit area allow meaningful ranking.

Water is an important constraint on bioenergy production in many locations. The impacts of water use are usually not included in LCA by lack of data and agreed methodology for estimating the water footprint [68,69]. Incorporation of location and time-specific data (*e.g.* for water use) in LCAs is a considerable challenge [70]. The eco-scarcity method includes eco-factors for water use. There is currently also no agreed methodology for estimating the impacts of biodiversity in LCA.

Standardisation of impact assessment methods is difficult [71]. Weighing methodology to aggregate LCA results in different environmental impact categories to one cumulative index has been described [72,73]. Pennington et al. [74] have proposed normalised potential environmental impacts (PEIs). Different evaluation methods in LCA use various policy criteria (Eco-scarcity, Eco-indicator 95, *etc.*) or monetary criteria (ExternE, EPS) and all focus on different impacts [75]. The EPS method [76] concerns more resource depletion than emissions.

4. Life-cycle assessments of global soy biodiesel pathways

Recent life-cycle assessments of soy biodiesels are reported in Table 1 and are discussed below on the basis of geographic denominations. Regular updates of LCAs [29,37,50] are useful in the light of improved agricultural practices determining a rise in soybean yield, different energy efficiency and emissions data for fertiliser production, as well as new industrial technologies. The most recent LCAs are best representing the state-of-the-art. Also, LCA methodology and data are continuously being improved. In the future, more attention should be paid to the effects of land use and allocations, particularly in scenarios of extended biodiesel mandates.

The LCAs reviewed differ in cultivation practices, business models (stand-alone crushing/refining or annex biodiesel plant), transesterification strategy, production strategy (plant size), energy mix, land use, markets, *etc.* LCA studies reported vary considerably from each other regarding assumptions made on agricultural yields, treatment of agricultural residues and allocation methods for high-value by-products. Both low and high soybean yield scenarios were reported (*cf.* Tables 12, 16, 20 and 30). Other issues evaluated considered the effect of land-use change [4,38,64,65] as well as soy biodiesel exports [38,82].

Several co-products are generated in producing biodiesel from oilseed. Main co-products are protein meal (co-produced during oil extraction) and glycerine (a by-product of industrial processing). The most valuable agricultural co-product in the soy biodiesel life cycle is soybean meal (SBM), which can be used as animal fodder or alternatively for direct combustion or for generation of biogas. Soymeal may replace rapemeal. Soybean meal dominates the protein meal sector for animal feed with about 67% of total production; the next largest product is rapeseed or canola

meal with 14%. Large-scale feedstock production could lead to an excess of meal, thus affecting the fodder market.

At variance to cereal straw, stubbles from soybean cultivation are seldom harvested as fuel but mostly left on field to increase soil organic matter (SOM). Alternatively, the residues may be utilised as a biofuel in vegetable oilcrop cultivation practices and should then be regarded as a co-product (to be allocated).

The proportion of bioglycerine produced depends on the feedstock composition but is typically about 10 wt% for refined vegetable oils. Glycerine is generally a low-value co-product of vegetable oil transesterification, although some industrial processes enable production of refined glycerol. In small-scale plants, glycerine is usually treated as an industrial waste and sent to hazardous waste incinerators or sold on to refineries. When biodiesel is produced on a large scale, the glycerine by-product is often refined in an energy-intensive process and sold to the pharmaceutical industry [86]. Very large-scale biodiesel production creates a glycerine glut. Already the co-product glycerine no longer makes a good market value. Efforts are being undertaken for its valorisation [87]. The energy used to produce biodiesel is to be allocated to biodiesel and its co-products.

4.1. North American soy biodiesel

The US Environmental Protection Agency (EPA) proposals for the 2012 requirements under the Renewable Fuels Standard (RFS2) are as follows: biomass-based diesel (1 Bgal, 0.91%), advanced biofuels (2.0 Bgal, 1.21%), cellulosic biofuels (3.45–12.9 Mgal, 0.002–0.010%), total renewable fuels (15.2 Bgal, 9.2%). The United States has registered a record biodiesel production of 3.2 billion L (mainly from soybeans) in 2011 and is now world's top producer. The dramatic increase in US biodiesel production is due to a government mandate in mid-2010 that required refiners to blend 3.1 billion L (800 million gal) of biodiesel with diesel in 2011. The US has set a target of 36 Bgal biofuels by 2022. At present, biodiesel production is aimed primarily at the internal market, although exports to the EU have been the main driver in the past few years. However, lately US biodiesel exports to Europe have dropped considerably from 1 Mt (2007) to 250 kt in March–December 2009 and to only 150 kt in January–September 2010.

US soy biodiesel based on Midwestern soy is well characterised by succession of LCAs. The first comprehensive life-cycle inventory (LCI) of biodiesel produced in the US from conventional soybean oil was published by Sheehan et al. [29] using mostly 1990 data and consequently does not reflect the latest innovations. The transesterification data were based on an old (1994) commercial facility. The following breakdown of the fossil energy requirements for the soy biodiesel life cycle was found: agriculture (no liming) 21.1%, crushing 25.6%, oil conversion 48.5%, and transport 4.8%. Biodiesel conversion uses most energy, accounting for about 56% of the total energy required in the life-cycle inventory. The results differ considerably from rape biodiesel where the agricultural stage is most energy consuming [16]. A net energy ratio of 3.21 was reported, to be corrected to 3.0 as the energy allocation for soybean oil was found to be only 13.7% of the total energy used in soybean agriculture, whereas soybean contains 18.4% oil [51]. Sheehan et al. also assumed a grossly incorrect glycerine product yield (212.8 kg/t BD) (also in GREET). Soy biodiesel reduces net CO_2 emissions by 78% compared to petroleum diesel [29].

Various LCA studies of soy biodiesel produced in US conditions have revealed great differences in farm inputs, oil extraction and biodiesel conversion (based on superseded data for crushing, transportation, and transesterification), co-product evaluation, assumptions about embedded energy, definition of the net energy ratio (NER), and inconsistent system boundaries. As a result, considerable discrepancies have been reported for NERs of SME. The energy balance of soy biodiesel production has critically been reviewed by Pradhan et al. [51].

The energy input for soybean agriculture varies from 4032 MJ/ha to 15,506 MJ/ha (Table 2). Considering average biodiesel production from soybean agriculture of 497 L/ha [90] and biodiesel energy content of 32.5 MJ/L the biodiesel energy produced from 1 ha of soybean is 16,152.5 MJ. This value obviously depends on the assumed value of the soybean yield per acre. Assumed soybean crop transport distances varied considerably in various studies: from 50 mi (80 km) [88] and 75 mi (120 km) [29] to an excessive 621 mi (1000 km) [84]; other models did not assume any energy for transportation. However, the impact of local soybean transportation is only a small fraction of the total energy input. Only the NREL study [29] also included energy for soybean oil transportation over 571 mi (920 km), *cf.* Table 2. Although there are large differences in the agricultural inputs, the fraction of total energy input assigned to biodiesel (biodiesel share of energy) has the greatest impact on the final results (Table 2).

The energy input for oil extraction has been reported to vary from 4611 MJ/ha [88] to 7938 MJ/ha [29]. Fuel use (including electricity) is the major energy input for soybean oil extraction. Crushing data used in various studies [29,84,88] are now outdated. Only Pimentel's model [84] included secondary energy inputs for infrastructure (equipment, construction). The energy input for transesterification varied from 2477 MJ/ha [29] to 4050 MJ/ha [88] (Table 2). Both models were based on old oil processing data (1993/1994). Biodiesel transportation from production facility to the pump over a maximum distance of 100 mi (160 km) was assumed [29].

The fossil energy ratio (FER) is also called energy balance. Without a significant increase in agricultural inputs FER increases with crop productivity. A major cause for the contradictory FER results of Refs. [20,29,44] is the difference in the amount of energy allocated between soybean oil used to make biodiesel and soybean meal. Pimentel's study [84], which claims a negative energy balance, is flawed by erroneously assigning only 19.3% of the total energy to soybean meal, whereas in reality 82% of the soybean mass goes into meal, by grossly overestimating lime use, by omitting energy used for transesterification (*cf.* Table 2), and by assuming an excessive crop transportation distance (1000 km). It is noticed that liming in the US soybean agriculture system, averaged over 19 major soybean-growing states, amounts to only

Table 2
Categorised total energy inputs of US soybean oil biodiesel production.

Production stage	Ahmed et al. [88]	NREL [29]	Pimental et al. [84]	GREET [89]
Soybean farming				
Energy use (MJ/ha)[a]	4031.78	7651.22	15,505.90[b]	5567.54
Biodiesel share of energy (%)	18.80	13.7	80.36	62.10
Soybean transport (MJ/ha)	63.44	378.77	167.37	587.77
Soil oil extraction				
Energy use (MJ/ha)[a]	4611.23	7937.50	7251.07	6461.14
Biodiesel share of energy (%)	18.80	18.00	80.40	62.10
Soy oil transport (MJ/ha)	–	717.28	–	–
Transesterification				
Energy use (MJ/ha)[a]	4050.29	2476.90	–	3316.74
Biodiesel share of energy (%)	90.20	90.00	–	79.60
Biodiesel transport (MJ/ha)	31.72	71.89	–	143.35

[a] Except for energy allocation.
[b] 9614.2 MJ/ha after correction for lime application.

463.7 kg/ha [50], quite opposed to the assumption of 4800 kg/ha made by Pimentel et al., *cf.* also Refs. [91,92]. Therefore, a net energy gain should have resulted for the agricultural stage.

Different definitions are used in the literature for the net energy ratio (NER) to measure the renewability of biodiesel. Considering that the soybean meal co-product is not used for energy the definition according to the NREL model [29], as

$$NER = E_b / E_1 f_1 + E_2 f_2 + E_3 f_3 \tag{3}$$

where E_b is the calorific value of biodiesel, E_1, E_2 and E_3 are the energy inputs for the agricultural, crushing and transesterification stages, respectively, and f_i are the corresponding fractions of the energy inputs attributed to biodiesel, was judged to be the most appropriate [51]. The mass *cq.* energy fractions for the agricultural, crushing and transesterification phases attributable to biodiesel are f_1 0.18/0.32, f_2 0.90/0.88, and f_3 1.00/1.00, respectively [51]. The standard definition of NER according to Eq. (3) includes fossil energy required for soybean seed production (not calorific value). A unified system boundary was developed for energy input in the biodiesel life cycle that includes energy associated with inputs (fuel, agrochemicals, electricity, *etc.*) used in production, processing and transportation, energy associated with the infrastructure (steel, cement, machinery, *etc.*) but excludes renewable energy (such as solar or hydroelectric) and seed energy (solar) and human labour energy [51]. Co-products could share the energy input according to their mass fraction (for renewability analysis) or economic value (for analysing the economic viability). The renewability of biodiesel depends strongly upon the amount of fossil energy required to produce the biodiesel. Soybean biodiesel is both renewable (NER 2.55) and economically sustainable (ESR 4.43) [93]. The economic sustainability ratio (ESR), defined as the ratio of the economic value of the output energy to its share of the economic value of the input energies, gives an estimate of whether a bioenergy system can be self-sustaining at given market prices for different energy sources. The main bottlenecks in soy biodiesel production are relatively low oilcrop yield (about 2.7 t/ha) and low oil content (18%) and the energy intensive oil extraction process. Soybean yield (in bu/ac) is a key factor in life-cycle analysis because it will affect energy use and fertiliser use per bushel of soybean harvested.

The life-cycle energy balance of soybean biodiesel production requires regular re-evaluation with updated data for soybean crushing, oil transport, transesterification, and biodiesel transport (*cf.* Refs. [37,46,50,52]). Pradhan et al. [37] have modelled soybean cultivation with processing in a crusher annex medium-sized biodiesel conversion unit (9.8 Mgal/yr) using 2002 data with mass allocation. Table 3 summarises the combined total energy requirements for the various process steps: 8.49 MJ/kg BD for feedstock production, 7.34 MJ/kg BD for crushing, oil extraction and drying of soybean meal, 5.95 MJ/kg BD for transesterification, recovery of excess methanol and glycerine treatment, and 0.32 MJ/kg BD for transportation of biodiesel to final destination. Mass-based co-product allocations were set as follows: for the agricultural stage: meal/oil 79.4/20.6; and for the conversion of degummed soybean oil: biodiesel/glycerol 82.4/17.6. All the energy use to transport biodiesel is allocated to biodiesel. As shown in Table 3, the total energy required to produce 1 kg of soy biodiesel in 2002 is 8.15 MJ/kg BD as compared to 11.55 MJ/kg BD in 1990, distributed as follows: biodiesel conversion, 60.2%; agriculture, 17.7%; soybean crushing, 15.3%; and biodiesel transport, 6.8%. The net energy value (biodiesel energy output minus fossil energy input) is 28.99 MJ/kg BD. The estimated FER of US biodiesel in 2002 is 4.56, or a 42% improvement over 1990 [37]. The model used by Sheehan et al. [29] separated the crusher from the biodiesel conversion plant and their inventory required transport of soy oil to the biodiesel plant over 571 mi, requiring 0.31 MJ/kg BD.

Table 3
Base case energy use for biodiesel and FER with co-product allocation and adjusted by energy efficiency factors.

Life-cycle inventory	Fossil energy use	
	Total (MJ/kg BD)	Biodiesel fraction (MJ/kg BD)
Feedstock production	8.49	1.44
Soybean transportation	1.36	0.23
Soybean crushing	7.34	1.25
Electrical and thermal energy	6.84	1.16
Hexane	0.50	0.08
Biodiesel conversion	5.95	4.90
Electrical and thermal energy	2.16	1.78
Methanol	3.37	2.78
Other chemicals	0.42	0.35
Biodiesel transportation[a]	0.32	0.32
Total energy input for biodiesel adjusted for co-products		8.15
Biodiesel total energy output		37.14
Net energy value		28.99
Fossil energy ratio (FER)		4.56

After Ref. [37].
[a] Based on 335 mi.

When this energy is added to the 2002 inventory of Ref. [37], FER declines from 4.56 to 4.41. Secondary inputs for both farm machinery (1.61 MJ/kg BD) and building materials (0.04 MJ/kg BD) decrease FER from 4.56 to 4.40. Lime use with an application rate of 358 lb/ac accounts for only 0.22%. With a projected increase in soybean yield from 38 bu/ac in 2002 to 45 bu/ac in 2015 FER will increase to 4.69. Moreover, during oil conversion to biodiesel 82% of the input mass of oil was assigned to biodiesel and 18% to the crude glycerin co-product (a more appropriate ratio is 89/11). Water consumption (excluding evapotranspiration) was found three orders of magnitude higher for biodiesel than for petrodiesel, which is not surprising because water is used for growing the crop and for washing at various steps in the production process.

Several factors have contributed to the considerable improvement in FER value from 1990 to 2002: (i) a 41% reduction in fossil energy inputs for soybean agriculture (from 2.44 to 1.44 MJ/kg BD), primarily due to less fuel, fertiliser and chemical usage, reflecting no-tillage practice and the adoption of GE soybeans; (ii) a 58% reduction in energy (electricity and natural gas/steam) required for crushing (from 2.96 to 1.25 MJ/kg BD); and (iii) a 12% lower energy requirement for transesterification (from 6.67 to 5.95 MJ/kg BD). Conversion of soybean oil by transesterification has become more energy efficient by an increase in larger biodiesel facilities (from 11.2 Mgal/yr on average in 2007 to 16.3 Mgal/yr in 2010 [94]), use of heat integration technologies, improved catalytic technology, and elimination of waste water treatment by reclaiming and reusing the wash-water stream to purify biodiesel. Two-thirds of the total waste water flows (typically 0.36 L/kg BD) in the biodiesel life cycle (80% lower than those of petroleum diesel) come from the soy oil conversion process. Table 4 summarises the trends in soy biodiesel production. Soybean yield is a key factor in LCA because it will affect energy use and fertiliser use per bushel of soybeans harvested. The amounts of fertiliser used (N, P, K) per bushel of US soybeans did not change significantly in the 1990–2010 period and are typically 61.2 g N/bu, 186.1 g P/bu, and 325.5 g K/bu.

A more recent LCA using mass-based allocation, based on 2006 data, reflects current soybean production and biodiesel plants built after 2002, which constitute the majority of US biodiesel producing units today [50]. The business model used to estimate the

Table 4
Trends in soy biodiesel production.

Production stage	Time-frame	Variations
Agricultural		
No-till practice	1990–2000–2006	10–33–45% acreage
Use of GE soybeans	1990–2002–2007	0–75–93%
Fertilisers	1990–2010	No
Herbicide use	1990/94–1995/99–2000/04	1.18–1.11–1.09 lb/ac/yr
Environmental impact coefficient (EIQ)	1990–2007	18.3[a]-15.3[b]
Soybean yield	1950–1990–2002–2007–2015	21.7–34.1–38.0–41.7–45 bu/ac
Crushing		
Oil extraction rate	1990–2002–2007	10.16–11.39–11.55 lb/bu
Solvent loss	1970–2009	66% reduction
Efficiency of electricity generation	1990–2007	32–33.71%
Conversion		
Plant size	1990–2010	Larger facilities
Heat integration technologies	> 2000	
Catalytic technologies	> 2000	Heterogeneous catalysts
Waste water treatment	> 2000	Re-use of wash-water streams

[a] Alachlor.
[b] Glyphosate.

energy required for conversion of soybean oil into biodiesel consisted of a soybean processing plant combined with a transesterification unit of 38.6 ML (10.2 Mgal or 34 kt/yr) nameplate capacity.

Studies over different time periods referring to the same geographical area may be used to illustrate changes in the energy life cycles over time. The fossil energy ratio (FER) has increased from 3.21 (1990) [29] to 4.56 (2002) [37] and 5.54 (2006) [50]. The improvements are primarily due to improved soybean yields and more energy-efficient soybean crushing and conversion facilities. Petroleum diesel yields only about 0.84 units of energy per unit of fossil energy consumed.

US soybean producers have been able to decrease their total energy use over time. At the same time, soybean yield has increased. Yield plays a critical role in the FER calculation. For every 100 kg/ha (1.5 bu/ac) increase in soybean yield, FER increases by about 0.76%. US average annual soybean yields have increased from 2293 kg/ha (34.1 bu/ac) in 1990 to 2885 kg/ha (42.9 bu/ac) in 2006, or about 33.6 kg/ha (0.5 bu/ac) per year without a significant increase in other agricultural inputs. USDA projects similar annual increases through 2017 [95]. Soybean yields have been improving over time because of new seed varieties (notably GM), improved fertiliser and pesticide applications, and new agricultural management practices [96]. The most significant change in US soybean production since 1990 has been the introduction of genetically modified soybeans. Genetically engineered soybeans with herbicide-tolerant and pest-management traits increase yields through improved weed and pest control. Using GM soybeans also reduces average pesticide use (typically 1.22 kg/ha, 1.09 lb/ac) and cost. Some herbicides are also less toxic today. Modern glyphosate is about 10 times less toxic than alachlor. Consequently, the environmental impact quotient (EIQ), which encompasses eleven different types of toxicity measurements and environmental impacts, is more favourable for glyphosate (EIQ = 15.3) than for alachlor (EIQ = 18.3). Agricultural data (1990) by Sheehan et al. [29] did not include GM soybeans; in 2002 75% were GM soybeans and today over 90%. Another major agricultural change is the increased adoption of no-till practices by soybean farmers (on 10% of acreage in 1990 up to 45% in 2006). Thus, significantly fewer soybean acres require fuel for tilling. Lime use only accounts for 57.9 MJ/ha and lowers the FER by only about 0.3% [50].

Modern soybean crushing facilities are far more energy efficient than older plants. Typically, the US industry average oil extraction rate has increased from 0.169 kg/kg (10.16 lb/bu) in 1990 to 0.193 kg/kg (11.55 lb/bu) in 2007/2008. Newer extraction plants are more energy efficient due to the adoption of energy-saving technologies that reduce production costs. Moreover, since 2002 the US EPA has required soybean crushing plants to limit their hexane use (new industry standard) [97]. Hexane loss has decreased by two-thirds compared to the 1970 level [98]. Overall, the energy required for crushing fell from 2.6 to 1.1 MJ/L of biodiesel. Sheehan et al. [29] still reported 3.44 MJ/kg SBO in 1998.

The FER of biodiesel changes very little upon adding secondary energy inputs such as those for agricultural machinery and building materials for a biodiesel plant (3.6% reduction in FER). With a reduction of energy input in US soybean agriculture by 52%, in soybean crushing by 58% and in transesterification by 33% per unit volume of biodiesel produced over the 1990–2006 period, the total life-cycle energy required for biodiesel fell from 10.2 MJ/L in 1990 to 5.9 MJ/L of biodiesel in 2006, *i.e.* a reduction of 42%.

Further improvements of FER of soydiesel over time are likely because of increases in soybean yields and the development of more energy-efficient technologies. For instance, continuous changes in the soybean crushing industry are expected to reduce the energy requirement for biodiesel production. Typically, soybean crushing requires a total of 6.3 MJ of fossil fuel, and conversion of soybean oil into biodiesel (including recovery of excess methanol and treatment of glycerine) requires 4.0 MJ/L of biodiesel produced. The increase in larger biodiesel facilities over the past years has reduced energy costs. Larger plants can also more easily justify adding energy-saving technologies (*e.g.* capture and reuse of heat, previously discharged). Reclaiming and reusing the wash-water stream used to purify biodiesel eliminates the need for waste water treatment. Improvements in catalyst technologies to produce biodiesel have resulted in higher conversion efficiencies of soybean oil into biodiesel.

Total life-cycle energy input in US soybean agriculture (2006) is typically of the order of 3590 MJ/ha, or equivalently 6.0 MJ/L of biodiesel produced [50]. Transporting biodiesel via marketing outlets to final destination requires about 0.3 MJ/L of biodiesel, for a total distance of 540 km (truck, barge, rail). Typical fossil energy use (MJ/L of biodiesel) for US soydiesel is made up of the following contributions: soybean production (1.0), transport (0.2) and crushing (1.1), and biodiesel conversion (3.3) and transport (0.3), totalling 5.9 MJ/L. For a biodiesel total energy output of 32.7 MJ/L the fossil energy ratio (FER) is 5.54 for 2006 production data.

Using 2006 data Huo et al. [44,47] compared the life-cycle energy and GHG emission impacts (CO_2, CH_4 and N_2O, with IPCC relative GWPs of 1, 23 and 296, respectively) of soy biodiesel and two soybean-derived renewable fuels (‘SuperCetane’ [99] and Green Diesel [100]) using displacement and different allocation

approaches to address the co-products. The LCA was much less detailed than that of Sheehan et al. [29]. The following assumptions were made. Yield (2006) was set at 42.5 bu/ac on about 75 M acres of harvested soybean area. In US conditions the total energy use for soybean farming was estimated to be 22,084 Btu/bu: 64% diesel, 18% gasoline, 8% LPG, 7% natural gas (NG) and 3% electricity [101]. Fertiliser (NPK) use was taken as follows: 61.2 g N/bu, 186.1 g P/bu, and 325.5 g K/bu. To estimate N_2O emissions from soybean farming 200.7 g N/ha were added to the nitrogen fertiliser input in order to properly account for the total amount of nitrogen in soybean mass that is left in soybean fields [44]. GREET 1.8 applies a conversion rate of 1.325% for N_2O emissions. The total energy use values per gram of fertiliser produced are 45.9 Btu/g N, 13.29 Btu/g P, and 8.42 Btu/g K [44]. It is noticed that an (incorrect) glycerin yield of 0.213 lb/lb of BD (GREET value) was used in Ref. [47] and an updated value of 0.116 lb/lb in Ref. [44], in conformity with Haas et al. [28].

With the displacement approach biodiesel offers 6% lower well-to-wheels (WTW) total energy consumption (TEC, comprising all energy sources, including fossil energy and renewable energy but excluding energy embedded in soybeans, which is eventually from solar energy) compared with low-sulphur petrodiesel (LSD), whereas 15–17% higher total energy use is found in case of two allocation approaches. Soy biodiesel achieves a significant reduction in WTW fossil energy consumption (FEC), which results from the fact that soybeans are a non-fossil feedstock. With the displacement approach soydiesel reduces WTW fossil energy use by 84% when compared with petrodiesel: for the allocation approaches the reductions are around 65–67%. Petroleum energy used in the soybean-based fuel cycles comes entirely from the WTP stage, primarily from diesel fuel used for farming equipment and from the trucks and locomotives needed to transport feedstock and fuel. For soybean-based fuels, PTW petroleum use is zero.

The transesterification process generates a much larger amount of diesel product and co-products from 1 t of soybeans than renewable diesels (CETC or Ecofining™ processes) but requires considerably more energy and chemical inputs than do other soybean-derived fuels. However, the latter options require energy-intensive hydrogen production. The energy content of all products involved in biodiesel production amounts to 16,149 Btu/lb, to be compared with 18,746 Btu/lb and 18,925 Btu/lb for the renewable diesels based on SuperCetane and UOP hydrogenation technology, respectively [44].

With the displacement approach soydiesel also achieves a significant reduction in WTW GHG emissions (94%), expressed in CO_2 equivalents, *versus* petrodiesel; with the allocation methods the reduction is more modest (68%) [47]. Other studies reported similar figures (72–80%) for reduction in WTW GHG emissions for soy-based diesel [29,103]. Land-use changes were not considered. The relative rankings of soybean-based fuels in terms of energy and environmental impacts vary under the different approaches accounting for co-products. The results underscore the importance of the methods used in dealing with co-product issues. Fig. 2 shows a lower aggregated environmental impact and CO_2 emissions for Green Diesel (hydrodiesel) than for either biodiesel or petrodiesel [102].

Kim and Dale [85] have evaluated the cumulative energy requirements (CER) and global warming impacts associated with soybean production (US, 2000 conditions). Production of soybean biomass requires a cumulative energy of about 2.01 MJ/kg. CER includes the energy requirement for producing fuel and the energy delivered by fuel. For soybean, with a low application rate of nitrogen fertiliser, the primary contributors to CER are diesel and gasoline use (> 65%), which accounts for direct use in the field, in transportation, and in upstream processes of fertiliser and agrochemical production. It is well known that agricultural production processes typically account for 21–44% of the total energy consumption in producing biofuels [29,104,105].

The global warming impact associated with producing soybean biomass is 161 g CO_2 eq/kg soybeans, excluding the carbon credit for carbon in crops. The primary source of GHGs in soybean production is again diesel use (> 50%). The primary greenhouse gas associated with producing soybeans (CO_2) contributes about 80% of the total global warming impact. For most crop production systems N_2O emission from crop cultivation is a major contributor to global warming. N_2O emissions released by decomposition of crop residues and nitrogen fixed by soybean were not included in the analysis because the conversion to N_2O of nitrogen in crop residues and fixed nitrogen is almost certainly affected by the subsequent crop and its cultivation practices. N_2O emissions depend on many factors such as soil nitrogen and moisture content, temperature, precipitation pattern, soil texture, nitrogen fertiliser application, and cultivation practices. For reliable estimates site-specific agricultural data are required.

Landis et al. reported a comprehensive agricultural inventory (LCI) – with mass-based allocation – of the corn–soybean agroecosystem (CTF, cradle-to-farm gate), representative of the US Corn Belt, taking explicitly into account energy flows from lime production and use, seed production and irrigation, fertilisers, the application of the soybean specific herbicide glyphosate and transportation of crop to mill [48]. Soy farming (40.5 bu/ac yield) includes the operation of machinery but not its embedded energy. Agricultural lime (aglime) is applied based on soil needs. Lime is used to decrease the acidity of agricultural soils. Soybeans require soil with a pH range of 6.0–6.5 [106]. It was assumed that no residues (*i.e.* stalks) are removed. Lime contributes significantly (17% of the total emissions) to NO_X emissions from vehicle and machine operations in soy production and should not be neglected in LCAs. Irrigation was accounted for only on corn crops (approximatively 14% of corn crops are irrigated with pumps in comparison with 8% of soybean crops). Manure as fertiliser was excluded from this study since on average only 6% of soybean crops and 18% of corn crops receive manure as a fertiliser supplement to synthetic fertilisers. Nitrogen and phosphorus are primary contributors to hypoxia and eutrophication in the United States [107,108]. Glyphosate-related emissions were allocated solely to soybeans since this specific pesticide is applied to over 80% of soybean crops and the remaining 16% receive a mix of over 30 different pesticides [109]. Soybean energy use was variously expressed as total energy 2.13 MJ/kg soy, fossil fuels 2.11 MJ/kg, and petroleum 1.73 MJ/kg. Total energy use by stage (percent) is as

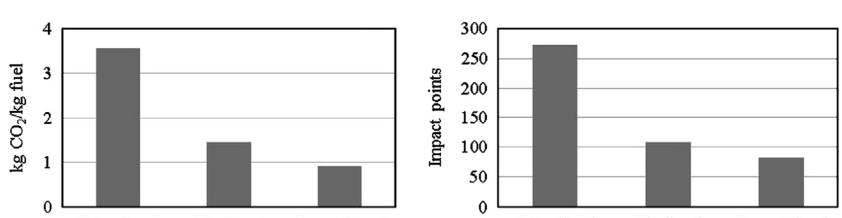

Fig. 2. Comparison of CO_2 emissions and aggregated environmental impact for petrodiesel, biodiesel and Green Diesel. After Ref. [102].

follows: soy farming (68), fertilisers (10), transportation (11), pesticides (3) and lime (8).

On-farm emission of N compounds (N_2O, NO, NH_3) makes up 99% of soy emissions. Soybean urban emissions constitute an important fraction with urban VOCs making up 25% of the total, CO 23%, SO_X 16%, NO_X 15%, and PM_{10} 12% of the respective emissions. While lime and glyphosate are important agrochemicals to consider in soybean production, irrigation and seed production contribute minimally (<0.002% to total energy). Results show that the dominant air emissions are from crop farming, fertilisers, and on-farm nitrogen flows.

Adler et al. [43] used the DAYCENT biogeochemistry model to assess soil GHG fluxes and biomass yields for the common corn–soybean (CS) and corn–soybean–alfalfa (CSA) cropping systems with conventional tillage (CT) and no-till (NT) in Pennsylvania, USA. Rotation schemes considered were CCS and CCCSAAAA. Crops in rotation have much lower biofuel yields than corn. Allocation to co-products was on the basis of the displacement method. Nitrogen fertiliser application rates were 12.7 g N/m^2 yr for corn (supplied in two batches). Nitrogen from soybean and alfalfa supplemented the first year of N applied to corn following the legume crops. In corn following soybean in CCS rotation, 3.7 of the 12.7 g N/m^2 yr was assumed to come from soybeans. In corn following alfalfa in the CCCSAAAA rotation scheme 8.7 of the 12.7 g N/m^2 yr was attributed to alfalfa. Both IPCC (2000) and DAYCENT methodology were used. IPCC (2000) bases N_2O emissions strictly on N inputs from fixation, fertilisation, and aboveground residue. In DAYCENT, N_2O emission also takes into account N inputs from decomposition of belowground residue and mineralisation of soil organic matter. This determines different estimates per crop.

Four sources of GHG were quantified: CO_2 emissions from manufacture of fertilisers, lime and pesticides, CO_2 emissions from fuel use by agricultural machinery, direct soil N_2O emissions, and indirect N_2O emissions from offsite denitrification of NO_3 and volatilised N that was deposited offsite and converted to N_2O in soil. For soybean cultivation fossil fuel energy requirements and CO_2 emissions for operation of agricultural machinery are 2.91 GJ/ha and 63.87 kg C/ha, respectively (CT), and 1.98 GJ/ha and 43.51 kg C/ha, respectively (NT), *cf.* Table 5. Corn–soybean–alfalfa rotation uses less energy than the corn–soybean rotation due to higher production of biomass relative to grain. Monoculture corn has higher SOC than corn–soybean rotation since soybean provides less residue input to the soil than corn.

N_2O emissions were the largest GHG source. Direct N_2O emissions according to IPCC (2000) were higher for corn–soybean–alfalfa rotation (29.7 g CO_2 eq/m^2 yr) than for corn–soybean rotation (24.7 g CO_2 eq/m^2 yr); different estimates were derived from DAYCENT (20.1 and 22.1 g CO_2 eq/m^2 yr, respectively). In this case IPCC (2000) overestimates N_2O emissions relative to DAYCENT. Soy biodiesel from corn rotations reduces GHG emissions by about 40%. Cellulosic energy crops have higher biofuel yield and lower GHG emissions per unit land area than corn rotations and have the greatest potential to reduce net emissions of energy use in the near- and long term [43].

Kim and Dale [58] have compared corn–soybean (CS) culture with various continuous corn (CC) cropping systems. More than 90% of corn stover in the United States is left in the fields. The CS rotation pathway produces corn-based ethanol and soy biodiesel; by-products, allocated by system expansion, comprise soybean meal, soapstock (in small quantities) and glycerine. The potential WTW environmental impacts associated with cropping systems over a 40-year cultivation period are given in Table 6. Carbon credits due to changes in soil organic carbon (SOC) are 32 Mg CO_2/ha for CS; 54 Mg CO_2/ha for CC. Corn stover removal reduces SOC accumulation rates, but cultivation of winter cover crops, even with corn stover harvest (CwC70), increases SOC accumulation rates because of increased carbon inputs from winter cover crops. The CS cropping system has negative environmental impacts in terms of non-renewable energy consumption and global warming impacts. The lower global warming impact of CS culture as compared to CC is due to lower agronomic inputs and less fuel consumption. The CC50 cropping system is characterised by high fuel consumption and low credits due to changes in SOC levels. The cropping system with winter cover crops (wheat) and 70% corn stover removal (CwC70) consumes the most energy. CwC70 combines a significant increase in SOC levels and lower N_2O emissions from the soil. Benefits of corn stover removal are therefore: (i) lower nitrogen related environmental burdens from the soil; (ii) higher ethanol production rate per hectare; and (iii) energy recovery from lignin-rich fermentation residues. Disadvantages are: (i) lower accumulation rate of SOC; and (ii) higher fuel consumption in harvesting corn stover. Planting winter cover crops can compensate for some disadvantages (*i.e.*, SOC levels and soil erosion) of removing corn stover.

All the cropping systems have negative GHG emissions. The CS rotation system has the lowest global warming credit because of a lower ethanol production rate, but the better acidification and eutrophication profile (*cf.* Table 6). The CS cropping system has also the lowest eco-efficiency (defined as ratio of product value to operating cost/environmental impact ratio) because its ratio of product value to operating cost is reduced due to a lower ethanol production rate. In other words, CS is less sustainable and provides less economic value per unit of environmental impact. Utilisation of corn stover and winter cover crops improves the eco-efficiency of the cropping systems. For the US soybean-based biodiesel pathway a net sequestration of carbon in arable soils was observed, confirming other studies [43].

Hill et al. [20] have compared soy biodiesel and corn ethanol. Soybean farming data referred to the 2002–2004 period assuming a biofuel conversion efficiency of 544 L/ha for soybean biodiesel; energy allocation was applied. A low glycerin yield of 0.08 lb/lb of

Table 5
Fossil fuel energy requirements and CO_2 emissions for operation of agricultural machinery (yearly averages).

Crop[a]	Conventional tillage, CT		No-till, NT	
	Energy (GJ/ha)	CO_2 emissions (kg C/ha)	Energy (GJ/ha)	CO_2 emissions (kg C/ha)
Corn	6.23	127.60	5.19	104.76
Soybean	2.91	63.87	1.98	43.51
Corn–soybean[b]	5.12	106.36	4.12	84.34
Corn–soybean–alfalfa[c]	3.26	68.28	2.76	57.17

After Ref. [43].
[a] C, corn; S, soy; A, alfalfa.
[b] CCS rotation.
[c] CCCSAAAA rotation.

Table 6
Potential impacts of the cropping systems for a 40-year cultivation period.

Impact category	Unit	CS[a]	CC[b]	CC50[c]	CwC70[d]
Non-renewable energy	GJ/ha	461	718	804	908
Global warming impact	kg CO_2 eq/ha	23,049	28,124	55,388	11,984
Acidification	moles H^+ eq/ha	55,146	82,120	83,540	88,482
Eutrophication	kg N eq/ha	91	136	137	135

After Ref. [58].
[a] Corn–soybean, no winter cover crop, no residue harvest.
[b] Continuous corn, no winter cover crop, no residue harvest.
[c] Continuous corn, no winter cover crop, 50% residue harvest.
[d] Continuous corn, winter cover crop (wheat), 70% residue harvest.

BD was assumed. At a soybean yield of 2661 kg/ha for soybeans and corn grown in rotation, using US annual averages for fertiliser and pesticide application rates and 4.89 kg soybeans crushed per litre of biodiesel produced, farm energy inputs into soy biodiesel production were 17.99 MJ/L. Conversion of biomass to soy biodiesel requires far less energy than for corn grain ethanol (0.273 MJ/MJ *vs* 0.797 MJ/MJ).

As shown in Table 7, both soy biodiesel and corn grain ethanol production result in positive net energy balances (NEBs), *i.e.* biofuel energy content exceeds fossil fuel energy inputs. NEB for corn grain ethanol is smaller than that for soy biodiesel. The low NEB value for corn grain ethanol is on account of the high energy input required to produce corn and to convert it to ethanol and its DDGS co-product. The NEB advantage of soy biodiesel is robust, as shown for various allocation modes.

The life-cycle GHG emissions of soy biodiesel (49 g CO_2 eq/MJ), derived from crops harvested from land already in production, are 59% those of diesel fuel; converting intact ecosystems to production would result in reduced GHG savings or even net release from biofuels production. Low levels of biodiesel blended into diesel reduce emissions of VOC, CO, PM_{10} and SO_X during combustion, and biodiesel blends show reduced life-cycle emissions for three of these pollutants (CO, PM_{10} and SO_X) relative to diesel [29].

Soybean biodiesel has major advantages over corn grain ethanol. These advantages stem from lower agricultural inputs and more efficient conversion of feedstock to fuel. Soy biodiesel (NEBR = 1.93) provides 93% more usable energy than the fossil energy needed for its production, reduces GHGs by 41% compared with diesel, reduces several major air pollutants and has minimal impact on human and environmental health through N, P and pesticide release. Corn grain ethanol (NEBR = 1.25) provides smaller benefits through a 25% net energy gain and a 12% reduction in GHGs.

Biofuels provide greatest benefits if produced with low agricultural input (energy, fertiliser, pesticide, lime) on land with low agricultural value, and require low-input energy to convert feedstocks to biofuel. Soybeans require fertile land and considerable agricultural inputs (except for N fertiliser).

The United Soybean Board (USB) has recently promoted an LCA study of soybean production and of soy industrial products using agricultural and transport data from 2001 through 2007 and processing data 2008 [46]. In this study impacts of infrastructure and human activities were excluded but energy to grow seedlings was included. Mass allocation was used and a sensitivity analysis was conducted using economic allocation. Data for the agricultural processes to produce soybeans were based on average US soybean production practices (Table 8). The BNF contribution (typically 70 kg N/ha in soy agriculture inputs) was not considered. The average 2004–2007 yield of 1120 kg/ac (2766 kg/ha) was assumed. Biodiesel production data of Ref. [46] reflects approximately 37% of the US production volume rather than data obtained by process modelling on actual energy and materials consumption data from a very small number of plants using older technology, as reported in previous studies. For instance, data in the 1998 NREL report [29] for soybean processing to produce soy crude oil and meal were obtained from a single soybean processing plant. The USB study [46] reflects 50 soybean processing plants (data provided by the National Oilseed Processors Association (NOPA), 2008). Transportation aspects for each unit process were included as follows: materials transport to the field, 360 mi (truck); soybeans to crushing facility, 75 mi (truck); soy oil transport to biodiesel plant, 570 mi (diesel locomotive). For energy calculations the average US electricity grid was considered (53% coal, 16% natural gas, 20% nuclear, 3% heavy fuel oil, 7% hydropower, and 1% other biomass).

The updated (2008) soybean processing data of Table 9 show that currently only 5236 kg soybeans are needed to produce 1000 kg oil, as compared to 5891 kg in 1998, which represents an 11% increase in efficiency. Over the same period the efficiency increase in soymeal production is 4% (from 1316 to 1267 kg soybeans for 1000 kg of meal).

Table 7
Net energy balance (NEB) and NEB ratio for soy biodiesel and corn grain alcohol.

Production system	NEB[a]	NEBR[b]
Process[c]		
Soy biodiesel	0.81	1.93
Corn ethanol	0.24	1.25
Product[d]		
Soy biodiesel	0.73	3.67
Corn ethanol	0.20	1.25

After Ref. [20].
[a] NEB, energy output−energy input (MJ/MJ).
[b] NEBR, energy output/energy input.
[c] Biofuel+co-products.
[d] Biofuels alone.

Table 8
Recent US soy agriculture inputs.

Inputs	Quantity per 1 t soybeans	Time reference
Energy inputs		
Diesel (farm tractor)	14.3 L	2007
Electricity	25 MJ	2007
Gasoline (farm tractor)	4.5 L	2007
LPG	32 MJ	2007
Natural gas	48 MJ	2007
Energy demand	763 MJ	2007
Material inputs		
Agrochemicals	0.52 kg	2001–2006
N fertiliser (NH_4NO_3 as N)	1.6 kg	2001–2006
P fertiliser (TSP as P_2O_5)	5.0 kg	2001–2006
K fertiliser (K_2O)	9.3 kg	2001–2006
Quick lime	94 kg	2002
Water (river)	15,855 L	1994, 1998, 2003
Water (well)	34,725 L	1994, 1998, 2003
Land use		
Cropland (conservation tillage)	2034 m^2/yr	2003
Cropland (conventional tillage)	850 m^2/yr	2003
Cropland (reduced tillage)	723 m^2/yr	2003

After Ref. [46].

Table 9
Soybean processing data (per 1000 kg oil).[a]

Inputs/outputs	Ref. [29] (1998)	Ref. [46] (2008)[b]
Energy inputs		
Electricity (kWh)	410	289
Heat (kcal)	2,865,000	1,502,729
Material inputs		
Soybeans (kg)	5891	5236
Hexane (kg)	11.9	2.96
Water (kg)	19.4	2547
Products		
Soymeal (kg)/(mass %)	4478/(82)	4131/(80.5)
Soy oil[c] (kg)/(mass%)	1000/(18)	1000/(19.5)
Air emissions (kg)		
Hexane	10.15	2.96
Water effluents (kg)	453	1383
Solid waste	46	8.7

After Ref. [46].
[a] Unallocated data.
[b] NOPA update.
[c] Degummed.

Table 10 summarises the environmental performance of both soybean and methyl soyate production (unallocated data). The output data from soybean production includes biomass CO_2 (−1,560,995 g/t soybeans) and N_2O (350 kg/t soybeans). Data of Table 10 are considered to be of high quality. However, the data are not specific for soy biodiesel but represent biodiesel plants for both soybean and canola oils. According to the National Biodiesel Board (NBB) little variation is found between plants that use these virgin oils, and soybean and canola oil require similar processing energy inputs. This is substantiated by Ref. [42], *cf.* Fig. 3. Reported petrodiesel/soydiesel ratios above 1 are in favour of soy whereas ratios below 1 are worse for soy (notably ecotoxicity, eutrophication and ozone depletion potential). For instance, a 0.50 ratio means that the petrodiesel impact value is only 50% of that of soy biodiesel. Where the results are negative values (as for GWP) no ratios can be used. Much of the GWP value stems from the carbon embedded in the product. Omission of BNF is likely to positively affect the GWP results and eutrophication impact.

Mass allocations for crushing operations of 1 t soybeans assumed a yield of 0.195 t crude soy oil and 0.805 t soymeal. For oil processing mass allocation was applied in the biodiesel:glycerin ratio of 89:11. A sensitivity analysis was carried out by using economic allocation on the basis of crude oil 38.5% and meal 61.5%. The results for economic allocation increase in all impact categories. This is expected since the soybean and crushing impacts increased from a nearly 20% allocation to nearly 40%. The GWP impact category is lower. Allocation change only affects the non-biomass CO_2 impacts. System expansion was not considered practicable as no data are available on an alternate soymeal process. Use of alternate protein meals is highly complex.

Table 10
Impact performance for soybean production and of methyl soyate *vs* petrodiesel (1000 kg output).

Impact category	Unit	Soybean production	Methyl soyate	Petro/soy
Global warming potential	kg CO_2 eq	−1.2E+03	−2.1E+03	–
Acidification potential	mmole H^+ eq	9.4E+04	4.1E+05	1.20
Eutrophication potential	kg N eq	2.9E+00	2.8E+00	0.16
Fossil fuel depletion	MJ surplus	1.9E+02	1.5E+0.3	4.87
Water intake	L	5.1E+0.4	4.8E+04	n.a.
Criteria air pollutants[a]	micro DALY	2.5E+0.1	1.1E+02	0.95
Ozone depletion potential	kg CFC-11 eq	8.0E−0.7	1.8E−06	0.09
Smog formation potential	g NO_X eq	2.0E+03	5.0E+03	2.04
Total fuel energy	MJ	1.8E+03	8.7E+03	0.93
Ecotoxicity	g 2,4-D eq	1.1E+0.4	1.4E+0.4	0.35
Human toxicity-cancer	g C_6H_6 eq	1.9E+02	7.5E+0.2	2.59
Human toxicity-Noncancer	g C_7H_8 eq	3.8E+05	1.0E+06	1.40

Unallocated data.
n.a. = not available.
After Ref. [46].
[a] CO, NO_2, O_3, SO_2, PM, Pb.

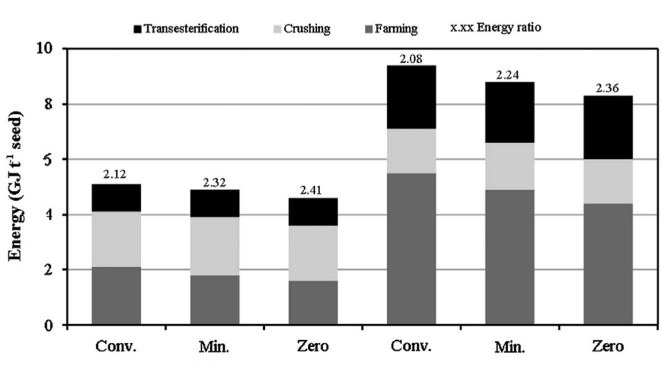

Fig. 3. Energy input and ratios for biodiesel production per tonne of soybean or canola seed for conventional, minimal and zero tillage conditions. After Ref. [42].

Canada cultivates soybeans on 3.1 M acres total. Canadian soybean agriculture is characterised by: (i) a high rate of GM adoption (59% in 2012); (ii) no need for pH adjustment through addition of lime due to the alkaline nature of most production soils; and (iii) energy-efficient production with low diesel fuel requirements and high adoption rate of no-till (55%) or minimal tillage (15–20%) agriculture [110]. This saves fuel, time and water. Energy consumption in soybean cultivation is low. In Canadian conditions the transportation distances (mainly rail) are rather high (typically 2000 km). The specific agronomic practices employed by Canadian soybean producers have a significant impact on GHG emissions. Very little soybean cropland is irrigated. Irrigation increases crop yield, but also energy consumption and N_2O emissions.

Smith et al. [42] have compared the energy balances of biodiesel production from typical soybean and canola agriculture practices in Canada using a system expansion approach. Per unit seed yield, farm production energy inputs for soybean are about three times lower than for canola (Fig. 3), mostly because of higher nitrogen fertiliser requirements for the latter. Energy required by processing and oil extraction, per unit oil, is higher for soybean. Differences in processing the oilseeds include drying of soybeans since the ideal moisture for flaking is less than that for storage; for canola mechanical press and hexane extraction are used as compared to only hexane extraction for soybeans. Energy required for transesterification per unit extracted oil is the same for both sources but for soy smaller amounts of oil need transesterification (*cf.* Fig. 3). The ratio of biodiesel energy produced per energy input was similar for both crops, namely 2.12–2.41 for soybean and 2.08–2.36 for canola (tillage dependent). Soybean requires less energy inputs, but also produces less oil than canola, for a given weight of seed. The estimated life-cycle energy inputs for soybean (3.9 GJ/ha) and canola (6.2 GJ/ha) – both for no-tillage systems – were similar to those reported by Mortimer et al. [111] for biodiesel from oilseed rape in the United Kingdom but lower than those reported for soybean by others [20,29,37,84,88], *cf.* also Tables 2 and 6, and only slightly superior to US 2006 data [30]. The lower estimate reflects the absence of liming and the use of lower tillage intensity; also energy used by farm personnel and in the processing industry was not included. Hill et al. [20] estimated this energy consumption to be about 37.7% of total soy biodiesel farm energy input. The estimated energy inputs were far below values reported by Venturi et al. [22] for agricultural practice in Italy (*cf.* Table 18). For zero tillage canola, a total of 4.53 GJ/t soybean was expended to grow and process the seed as compared to 8.31 GJ/t for canola. For a zero tillage farm plus crushing/extraction the energy input would need to increase to 10.9 GJ/t for soybean (+163%) and to 17.9 GJ/t for canola (+196%) before the output/input energy balance for more energy intensive farming and processing systems would decline to a break-even point. An allocation of energy used by individuals involved in producing and processing soybean and canola would still result in a positive energy balance for the biodiesel production. The co-product allocation affects the calculated energy balance. If no energy is allocated to protein meal, the output/input energy ratio declines to 1.52–1.70 for soybean and to 1.91–2.16 for canola. The relatively smaller decline for canola reflects a lower percentage for energy allocated to canola meal (11.9%) than to soybean meal (36.7%).

However, the energy balance remains positive without co-product allocation.

4.2. Brazilian soy biodiesel

There exists no standard model for soy in Brazil, where climatic and farming conditions are widely diversified (wet, dry, tropical; rich/poor soil; smallholder to mega farming, *etc.*). The diversity of Brazilian soybean cultivation and processing conditions would impose various life-cycle analyses. However, only few such studies describe environmental assessments of Brazilian soy biodiesel [4,66,79,80,112]. The usual soybean agricultural production methods in Brazil are characterised by intensive use of fertilisers (P, K), herbicides, lime, and agricultural machinery. Gazzoni has indicated a positive energy balance (1:4.76) [112].

Cavalett et al. have presented an LCA [80] and an integrated environmental assessment of soybean agricultural production (with conventional no-tillage management) to soydiesel transport to the consumer (WTP) in Brazil using different evaluation methods: Emergy Accounting (EA), Embodied Energy Analysis (EEA) and Material Flow Accounting (MFA) [79]. Emergy is defined as the sum of all inputs, expressed in equivalent solar energy, directly or indirectly incorporated (in the form of energy, matter, human or natural work) and required for the production of a given resource. Emergy accounting is particularly suitable for studies in agriculture. The embodied energy method focuses on the commercial energy flows and material flow accounting assigns more importance to material flows.

A soybean production of 2830 kg/ha/yr was reported with 510 kg crude soy oil. For 1 L of biodiesel produced 5.2 m^2 of crop area is required and 8.8 kg of topsoil is lost in erosion; 0.206 kg of fertilisers, 0.004 kg pesticides and 7.33 kg of abiotic materials are needed as well as 9.0 t of water and 0.66 kg of air whereas 0.86 kg of CO_2 are released. The latter figure translates into a release of 26.3 g CO_2/MJ delivered (*cf.* about 100 g CO_2/MJ delivered for commercial diesel production [34]). However, nitrous oxide emissions were not considered. Some of the material flows required for the specific Brazilian biodiesel production are remarkably high on a global scale, in particular fertilisers, abiotic materials and topsoil. It is noticed that in recent US conditions only 0.078 kg fertilisers per litre of biodiesel are required (Table 8).

Allocation of input flows to the products strongly affect EEA and MFA results. Even with a favourable allocation procedure (64% of the resources attributed to soymeal on energy basis), the environmental impacts of soy biodiesel are remarkably high. The emergy accounting (EA) method shows quantitatively that biodiesel from Brazilian soybean produced in the given conditions cannot be considered a totally renewable energy source. The soybean biodiesel production is strongly dependent on the use of non-renewable resources in the agricultural production, transport and industrial processing stages. The non-renewable emergy is 2.26 times higher than renewable emergy for soy biodiesel. The soy biodiesel emergy yield ratio (1.46) indicates that a very low net emergy is delivered, as compared to alternatives. The fraction of soy biodiesel that can be considered renewable is very low (about 31%), but this is still better than for fossil fuels (totally non-renewable). The soy biodiesel transformity (3.18E+05 $seJJ^{-1}$) is also higher than for fossil fuels (coal, natural gas, oil, gasoline and diesel) and other biofuels (sugarcane ethanol, sunflower biodiesel) and indicates that soy biodiesel presents a higher demand for direct and indirect environmental support and therefore a lower large-scale ability to convert resources into products than other energy sources. The natural processes producing fossil fuels have been globally more efficient than the human-driven process of soybean cropping for biodiesel.

The Emergy method can properly account for and quantify the renewability of biodiesel since it includes not only inputs and services from the economy, but also resources from nature, usually not considered in conventional energy evaluations. Renewable resources (such as rain) used in the agricultural phase account for only about 30% of the total resources used by the Brazilian soy biodiesel processes. Rain is the main renewable input used. The great amount of non-renewable resources used by the production process (limestone, 8.3%; topsoil losses, 7.65%; fertilisers, 5.65%) indicates the strong dependency from economic resources and, therefore, its vulnerability to the input's market prices and to the availability of fossil fuels.

The Energy Return on Investment (EROI), the amount of energy output divided by the energy invested by the economic system, offers an interesting overall energy cost evaluation of the biodiesel production. About 0.07 kg of crude oil equivalent is needed to produce one kg of soybean (EROI=7.24 J/J). Instead, 0.27 kg of oil equivalent is needed per litre of biodiesel produced (EROI=2.48 J/J). This value is lower than that (5.54) reported by Pradhan et al. [50] for US soy biodiesel on the basis of 2006 cultivation and production conditions and also lower than the value of 3.2 for US soydiesel produced using 1990 technology [29]. The EROI value also differs from literature values for soy biodiesel (0.7–1.6) [22]. The great differences in literature EROI values reflect different climatic conditions, crop yields, input utilised, management practices, and allocation procedures. The embodied energy analysis shows that biodiesel uses a large amount of fossil fuel energy in both the agricultural and industrial conversion stage. Fossil fuels present a much better EROI (about 10–15).

The agricultural production stage accounts for the largest amount of resources used in the life cycle of soybean products (soymeal, exported to Europe, refined soy oil and biodiesel) with 86.9% for biodiesel, followed by transesterification (7.9%) and crushing (5.1%). The agricultural and soy oil transesterification phases have the highest impact in the embodied fossil energy analysis, accounting for 41% and 42%, respectively, of the total energy inputs. Important contributors to transesterification are methanol (24.5%) and diesel fuel (16.3%). The results differ from modern US soydiesel production (2006) where contributions to fossil energy use (totalling 5.9 MJ/L) rank as follows: biodiesel conversion > crushing > soybean production > transport [50].

In view of the resources needed, production of biodiesel from Brazilian soy oil in the aforementioned conditions is not an environmentally friendly process. On the basis of material flow accounting (MFA), embodied energy analysis (EEA) and emergy accounting (EA) Brazilian soy biodiesel is more likely to generate environmental and social damages than to become a renewable energy source to society, despite a possible contribution to the CO_2 emissions [79]. The direct pollution (fertilisers, agrochemicals, pesticides) and other environmental impacts (soil loss, energy, material, water and land use) related to the net energy delivered indicate that such soybean biodiesel produces a high environmental pressure. Without careful design of biodiesel production systems the intensive exploitation of land and fossil fuel use may result in considerable environmental and social damages. Also the soymeal flows exported to Europe are responsible for highly negative environmental impacts in Brazil (environmental loading ratio of 2.83) [79,80]. This market requires an input equivalent of 3.31 Mt petroleum. Soy monoculture without or beyond control in Brazil causes high damage to the ecosystem. However, soybean can be produced in more sustainable alternative systems in order to reduce these negative aspects (Cooperbio).

Different aspects of land use related to soy biodiesel production have been discussed by various authors [4,66]. Reijnders et al. [4] have estimated the emissions of biogenic carbonaceous gases such as CO_2 and N_2O linked to the life cycle of Brazilian soybeans. Direct

replacement of rainforest and Cerrado by soybean production has been considered. It has been estimated that 703–767 Mg CO_2 eq/ha is emitted on conversion of tropical rainforest to arable land. For corn–soybean rotation on land that is cleared, half of the loss is to be allocated to soybean. Similarly, emission of GHGs on converting the original Cerrado into arable land amounts to an estimated 92–103 Mg CO_2 eq/ha. In cultivating soybeans there is also carbon loss from soils [113,114]. In the Cerrado region this C loss was estimated at $\sim$0.5 Mg/ha/yr for continuous zero tillage and up to 1.5 Mg/ha/yr for conventional tillage for the case of corn–soybean rotation with two crops per year [113]. Half of the yearly soil C loss is again to be allocated to soybean. Per soybean harvest there is a loss of 0.92 Mg CO_2/ha/yr for zero tillage and 2.75 Mg CO_2/ha/yr for conventional tillage. For the Amazon region 0.64 Mg CO_2/ha/yr was quoted [4].

For soybean production in Brazil the input of fixed N has been estimated at 170 kg/ha of harvested soybeans [115]. Emission of N_2O corresponds to 0.76–2.52 Mg CO_2 eq/ha soybeans. Using economic allocation about 45% of biogenic emissions linked to soybean cropping are on account of oil. The combined emission of biogenic GHG/kg biodiesel should not exceed 0.9 kg CO_2 eq for Brazilian soybeans when the requirement is not to perform worse than conventional diesel [4,82]. The values for biogenic carbonaceous gases and N_2O emissions (price allocation) when arable land takes the place of tropical rainforest or Cerrado, and remains in use for 10 or 25 years, assuming zero tillage, are 13.9–35.2 and 5.4–10.7 kg CO_2 eq/kg BD, respectively. Clearly, in the case of growing soybean on deforested land, the loss of the aboveground C stock in converting tropical forest into arable land has a major impact on the life-cycle GHG emissions of biodiesel. Righelato et al. [116] have argued that saving tropical forests is to be preferred over growing crops for biodiesel production.

Using no-till practices instead of mechanical tillage, use of cover crops and maximising the return of harvest residues to arable soils leads to higher soil carbon stocks and this lowers life-cycle CO_2 emissions of biofuels [117]. Life-cycle N_2O emissions of biofuels can be lowered by improving the N-efficiency of agriculture. Not cutting forests to generate arable land, but conserving soils so that they can be used productively for a much longer time helps to improve the environmental performance in Brazilian agriculture [118,119].

Mattsson et al. have dealt with the impact category land use in LCA studies and have compared Brazilian (Cerrado) soybean, Malaysian oil palm and Swedish rapeseed [66]. The selected indicators for land use comprise soil fertility (erosion, hydrology, soil organic matter, soil structure, nutrient balance, soil pH, heavy metals), biodiversity, landscape aesthetic value and land transformation.

Products from 1 ha each of soybean, rapeseed and oil palm acreage are shown in Table 11. The protein meal part of the whole soybean crop is too valuable to be considered simply a by-product. The calculated land use per tonne of product depends on the allocation method chosen for vegetable oils *versus* protein meal. If allocation by mass is chosen, an arable land use of 0.42 ha/t soymeal is required, as compared to 0.59 ha/t rapemeal. The annual soil erosion for Cerrado soymeal is 3300 kg/t as compared to 10–20 kg/t of Swedish rapemeal. Soybean cultivation in the Cerrado causes 8 t/ha/yr of soil loss [121]; *cf.* 0.03–0.05 t/ha/yr for Swedish rapeseed and 7.7–14 t/ha/yr for Malaysian oil palms.

Soil organic matter (SOM) is essential for supplying plant nutrients in poor soils. Organic matter (0.9–5%) is very critical in Brazilian soils (*cf.* 3–4% in Sweden) with their poor capacity to hold plant nutrients. Loss of SOM is a serious problem in vast soybean production areas of Brazil. Intense soil cultivation combined with the high soil temperature speeds up the degradation of organic matter (crop residues) [122]. In comparison, Swedish rapeseed crops do not offset the soil organic matter content in the soils; the same holds for oil palm plantations. The soybean case shows that the loss of soil organic matter is the most serious threat to suitable cultivation in the Cerrado.

Soil compaction, *i.e.* loss of pore space, renders soils less suited for plant production. This is presumably a problem in the Cerrado as a result of the use of heavy machinery. It is also a matter of concern in Sweden but not in oil palm plantations. Legumes such as soybeans lower the soil pH. Soil pH is of special concern in the Cerrado where the pH is already very low. Soil pH controls the availability of plant nutrients and micro-organisms, for instance the nitrogen-fixing bacteria that live in symbiosis with the soybean plant. Such bacteria are very sensitive to low pH values. Adding lime to Cerrado soil is a necessity for soybean cultivation [123].

A plant nutrient balance is essential since depletion of P and K in arable soil is a threat to long-term fertility. An excess of nutrients is applied to Cerrado soybeans. These excess nutrients either remain in the soil or are lost through erosion or leaching, diluted in runoff water or dispersed in other ways. Nitrate leakage and phosphorus losses during cultivation appear in the impact category eutrophication in LCA studies. Phosphorus and potassium are important for long-term fertility of the soil and are relevant in the land-use category. On the whole it appears that fertiliser application is rather well balanced with the output and that P and K content in Cerrado soil remains at a steady state. While in soybean cultivation phosphorus is eroded with the soil, rapeseed cultivation leads to nitrogen leakages. With regard to the soil content of the heavy metal cadmium (originating from phosphorus fertilisers), its application rate is 1000–2100 mg/ha/yr in Brazil; *cf.* 240 mg/ha/yr in Sweden and 3900 mg/ha/yr in Malaysia. Cadmium is removed from the soil through crop uptake and leaching [66].

Despite the wide variety of Brazilian soybean cultivation conditions there is a scarcity in LCAs which could be a rich source for agricultural improvement. Although Brazil is not a soy biodiesel exporter it is an important soybean/soymeal exporter to Europe and consequently needs to conform to the required sustainability standards.

Table 11
Products from harvested crops (t/ha).

Crop	Harvest	Crude oil	Protein meal
Soybean[a]	2.9	0.56	2.33
Rapeseed[b]	3.0	1.2	1.6
Oil palm[c]	19.1	4.8	0.7

[a] Soybean yield in Brazil. Allocation between oil and meal according to Ref. [46].
[b] Allocation according to Boulder [120].
[c] Total oil yield 25%.

4.3. Argentinean soy biodiesel

LCAs reflect feedstock and regional specificities. Results can vary considerably for different oilcrops, agricultural practices, land-use changes, energy mixes and transport distances. With the competitive position in the production of vegetable oil, the high efficiency throughout the whole value chain from low-energy crop production (including direct sowing techniques) to oil milling, vertical integration of vegetable oil and biodiesel producers (*e.g.* AGD and Vicentin), modern crushers annex biodiesel plants, and the existing infrastructure for transport, storage and export, there can be no doubt that Argentinean biodiesel has a net positive energy balance [124,125].

A recent INTA (National Institute for Agricultural Technology) report allows insight in the energy balance of biodiesel production in Argentina [39]. The study is based on various soybean agricultural practices in Argentine conditions (2008) (Table 12) and on (outdated) US processing conditions (1998) [29]. Total fossil energy use in the agricultural stage for best current Argentine soybean practice (7.7 MJ/L BD) is similar to that reported by Pradhan et al. [37] for US soybean production 2002, namely 8.49 MJ/kg BD (*cf.* Tables 3 and 13). However, the life-cycle input in Argentine soybean agriculture (4777–6995 MJ/ha) (Table 12) exceeds that of more recent (2006) US soybean agricultural data, namely 3590 MJ/ha or 6.0 MJ/L of biodiesel produced [50]. Minimum Argentine agricultural inputs (1382 MJ/t) also exceed those reported recently by USB (736 MJ/t) [46], *cf.* Tables 8 and 12. The WTP energy balance of Table 13 takes into account transportation of soybeans to the oil crusher annex biodiesel plant (1.43 MJ/L BD), industrial processing (8–15 MJ/L), and transport to the distribution centre (0.89 MJ/L). It was supposed that 1 t soybeans yields 190 kg oil and 170 kg biodiesel. Technological improvements in crushing and oil conversion (Table 4) have not been included by Ref. [39]. The reported net energy values of Table 13 are based on a relatively high estimate of the energy contents of biodiesel (LHV, 35.0 MJ/L); 32.7 MJ/L is more commonly used. Earlier findings that the energy balance for direct seeding is better than for conventional tillage farming [126] are not confirmed by Tables 12 and 13. The energetic values assigned to the co-products, which account for 70% of the energy generated, greatly influence the final results. Different methods are used in the literature to quantify the energy content of the co-products. INTA has used a conservative estimate (only the calorific value).

At present, Latin American countries are increasing the use of fertilisers – as in case of high tech soy 1 (Table 12) – in an effort to maintain a competitive edge in the world market. Direct seeding/high tech first-class soy shows the most favourable energy ratios among the various agricultural practices, namely 6.48 for product and co-products and 1.94 for biodiesel. The fertiliser efficiency of this practice exceeds that of conventional and direct-seeding first-class soybean.

Table 14 confirms the general low impact of fertilisers (about 2%) in Argentine soy cultivation practices and shows the large impact (on average 70% in indirect energy) of glyphosate and other agrochemicals.

Huerga et al. [40] have considered large-scale biodiesel production (100 kt/yr) based on direct seeding (DS) soy 1; processing data were based on Sheehan et al. [29]. Using the displacement method the agricultural stage requires 16.02 MJ/kg oil (or about 65% of total WTP energy consumption) and the industrial stage 7.06 to 8.05 MJ/kg BD (mainly on account of methanol and steam). The energy output/input ratio is 2.22. In view of the modern industrial infrastructure in Argentina it would be of considerable interest to have the energy balance of medium- and large-scale biodiesel plants based on actual processing data. INTA and an agricultural research station in Northwest Argentina are working on the life cycle and energy balance at farm level for traditional crops (soybean, sugarcane) and other products (castor bean, sweet sorghum).

Various estimates of GHG savings of typical Argentine biodiesel *vs.* fossil diesel have been reported: 30.8% (EU RED Annex V), 51% (JRC), 56% (ISCC) and 57% (E4Tech). INTA has also reported energy use and GHG emissions for soy biodiesel from feedstock produced on prior agricultural land using no-tillage practice [81]. Since 90% of soybean is originating from already agricultural land land-use change was not considered. Industrial conversion was modelled according to European values even though Argentine facilities are more modern with better overall efficiencies due to scale. Soy biodiesel produced with high fertiliser input leads to reduction in energy and GHG emissions compared to the reference diesel of 67.2% and 73.6%, respectively. GHG emissions amount to 0.0232 kg CO_2 eq/MJ LHV fuel and avoided emissions to 1.6 t CO_2/ha/yr. The GHG reduction meets EU RED requirements [11].

Argentinean biodiesel producers need to evaluate the environmental performance of their export product in order to comply with current sustainability criteria. Energy balance and GWP may severely be influenced in the occurrence of land-use changes (*cf.* Table 35). Panichelli et al. [38] have described an LCA of Argentine soy biodiesel for export to Europe with reference to a 2000–2009 time-frame. The paper also evaluates the position of Argentina as a producer of sustainable biodiesel in comparison with other producers (Brazil and USA for soydiesel; Malaysia for palm; and Germany and Switzerland for rapeseed). Land-use competition was explicitly taken into account as a relevant impact category. The biodiesel pathway was modelled from well-to-exportation port (WTE). As results can change significantly depending on the country of destination also export to Switzerland was considered

Table 12
Energy analysis for Argentine soybean agriculture.

Agricultural practice[a]	Direct energy[b] (MJ/ha)	Indirect energy[c] (MJ/ha)	Total energy (MJ/ha)	Hectare yield (t/ha)	Energy consumption (MJ/t)
CT soy 1	2000	4024	6024	2.80	2151.4
DS soy 1	1465	5531	6995	2.80	2498.2
DS/HT soy 1	1792	4427	6219	4.50	1382.0
DS soy 2	1229	3548	4777	2.20	2171.4

After Ref. [39].

[a] CT, conventional; DS, direct seeding; HT, high tech.

[b] Tillage, sowing, harvesting, transportation.

[c] Embedded in RR seeds, fertilisers and agrochemicals (herbicides, insecticides, fungicides, inoculants).

Table 13
Energy balance for Argentine soy biodiesel and co-products.

Agricultural practice[a]	Energy of agricultural stage (MJ/L BD)	Total fossil energy (MJ/L)		Energy ratios[b]	
		Min	Max	Min	Max
CT soy 1	12.0	22.32	29.32	1.57; 5.23	1.19; 3.98
DS soy 1	13.9	24.22	31.22	1.45; 4.82	1.12; 3.74
DS/HT soy 1	7.7	18.02	25.05	1.94; 6.48	1.40; 4.67
DS soy 2	12.1	22.42	29.42	1.56; 5.21	1.19; 3.97

After Ref. [39].

[a] CT, conventional; DS, direct seeding; HT, high tech.

[b] Ratio of renewable fuel energy output to total fossil energy input; ratio of total renewable energy output for products and co-products to total fossil energy consumption.

Table 14
Relative contributions (%) to total indirect energy (MJ/ha) for various soybean agricultural practices in Argentina.

Agricultural practice[a]	Seeds	Fertilisers	Glyphosate	Other agrochemicals
CT soy 1	29	3	–	68
DS soy 1	23	2	42	33
DS/HT soy 1	23	2	38	37
DS soy 2	38	–	28	34

After Ref. [39].

[a] CT, conventional; DS, direct seeding; HT, high tech.

and the system was modelled from feedstock production in Argentina to biodiesel use (WTW) as B100 in a 28 t truck. As soybean meal is a commodity with a defined market value economic allocation has been chosen but a sensitivity analysis of allocation methods (economical, energy and carbon content) did not greatly change the results.

Seed input varied from 70–80 kg/ha depending on the production method. In soybean production nitrogen input is composed of biological N fixation (BNF, 70 kg/ha) and N fertiliser. In Argentina nitrogen fertiliser is only applied to first-class soybean production, as monoammonium phosphate (5 kg MAP/ha); P fertiliser is applied as MAP and triple superphosphate (10.5 kg TSP/ha); K fertiliser was not applied. Soybean irrigation is not common practice in Argentina. Pesticide applications (in g active ingredient) are mainly glyphosate (2340 g/ha), chlorpyrifos (421 g/ha), and a variety of other herbicides (totalling 500 g/ha). Different scenarios were modelled to determine the impact of changing input in the agricultural and fuel production phase. The environmental impact is mainly determined by the agricultural phase and, consequently, by the soybean yield. A soybean yield of 2591 kg/ha (2000–2005) was an average over first- and second-class soybean in reduced and conventional tillage conditions [127]. A 10% soybean yield increase reduces GWP by 7% and the cumulative energy demand (CED) by 5%.

Land use was assumed being arable land and transformation from arable land, shrub land, pasture and forest. GHG emissions from deforestation were estimated as the emission from land provision and the emission from carbon stock change in soil, as implemented in ecoinvent®. Soybean was assumed to be cultivated in deforested areas during 2 years. CO_2 emission from carbon stock change in soil (55 t CO_2/ha/yr) and biomass (193 t CO_2/ha/yr) were taken from Gasparri [128]. Carbon loss from soil after deforestation was modelled as 15 t C/ha/yr [128]. Carbon stock change in soil represents only 7% of the total emission from land-use conversion. Emissions from biomass (93%) are accounted as provision of land by forest clearing. Carbon emissions from deforestation should be better accounted for when new data become available. Emissions from land-use change other than direct deforestation were excluded by lack of data.

The usual business model in Argentina is an integrated oil mill and transesterification plant. Soybean oil extraction requires drying (from 16% to 13% relative humidity) in the vegetable oil mill using natural gas. Solvent extraction (with methanol), based on international standard technology [129], typically allows extraction of 19% soybean oil. After transesterification, using average international technology, 972.7 kg SBO and 106.1 kg glycerine are obtained from 1 t soybean oil. Soybeans were transported over 30 km by tractor to regional storage. Transportation of soybeans to the mill (300 km) was modelled by truck (80%) and train (20%). Biodiesel was transported by truck from transesterification plant to port (100 km), by transoceanic tanker from Rosario to Rotterdam (12,091 km), by barge tanker to Basel (840 km) and to service station (100 km train, 150 km trucks). The impact of the transportation and utilisation phase is a function of transport distance and the type of vehicle used in each country.

The Argentinean soy biodiesel pathway, modelled from feedstock production up to exportation port, is more energy consuming in comparison with other regional biodiesel pathways (33.8 MJ/kg BD), yet below the fossil reference CED value. The SBME energy contents is 37.2 MJ/kg. The US has the best performance of both CED and GWP. The impact of Argentinean biodiesel production is largely dominated by the agricultural phase. Feedstock production represents 65% of CED and 85% of GWP. The agricultural phase of biodiesel production in Argentina and Brazil, where land change occurs, performs similar with respect to CED and GWP but differs from US soybean production, where the industrial phase is dominant with 56% for CED [50] and 54% for GWP [38]. Both CED and GWP values for the agricultural phase depend strongly on the type of feedstock and land use. Provision of scrubbed land is an energy-intensive process accounting for 83% (AR), 51% (BR) and 52% (MY) of CED in the agricultural phase. Without land clearing an Argentine biodiesel CED of 15.6 MJ/kg BD would result, mainly determined by the production and use of seeds and fertilisers, harvesting and ploughing. This value is not dissimilar from cases of EU and US (total fossil energy use of 6.6 MJ/kg BD) in 2006 conditions [50]. Biodiesel conversion would then use the most energy, accounting for about 56% of the total energy required in the life-cycle inventory, exactly as for US soy biodiesel. Use of methanol contributes significantly to the impact due to the transesterification (26% of CED for the Argentine soy pathway). However, methanol is not a parameter in the comparison of regional biodiesel pathways. The Argentine pathway results in the highest CED, GWP, AETP and HTP values compared to all reference biodiesels: soybean (BR, USA), rapeseed (EU, CH) and palm (MY). Compared with the fossil diesel reference all impact categories are higher for biodiesel from Argentina, except for CED (reflecting modern technology).

Environmental impacts vary. The soybean production methods have a strong influence on ecotoxicity. Terrestrial and aquatic ecotoxicity potential (TETP and AETP, respectively) increase significantly for conventional tillage by a combination of lower yields and higher herbicide (cypermethrin) input; land use (LU) is also increased as first-class soybean cultivation in conventional tillage does not allow crop succession. The reduced tillage methods (both for first- and second-class soybeans) reduce ecotoxicity. Land-use provision through deforestation for soybean cultivation has the highest impact for the GWP, CED and HTP categories of Argentinean biodiesel (*cf.* also Table 35). While N_2O emissions during fuel use are the main cause of acidification, nitrate leaching during soybean cultivation is the main contributor to eutrophication. Land use is almost totally affected by arable land use occupation for soybean cultivation. Almost the total impacts on TETP and AETP are on account of the use of cypermethrin (45 g/ha) in oilcrop cultivation. Cypermethrin use can be avoided by replacement with the much less toxic deltamethrin, resulting in a considerable reduction of TETP, AETP and HTP. The environmental impact of the system is mainly determined by the agricultural phase, and consequently, by the soybean yield. Yield increment lowers the environmental impacts. The total impact of the system is reduced (CED 5%, GWP 7%) by an increase of 10% in soybean yield, Recently, yields of 2905 kg/ha (+12%) have been reported.

Soy biodiesel produced in both Argentina and Brazil using deforestation practices shows a higher GWP value than rape biodiesel production [16] and exceeds the fossil reference (83.8 g CO_2 eq/MJ), mainly as a result of fertilisation and land-use change; consequently, it is not a good means to mitigate global warming. The default value of GWP is given by the UK Renewable Transport Fuel Obligation (RTFO) to calculate the GHG balance of imported biofuels [130], including soy biodiesel produced in Argentina. This value is less than half the result reported by Panichelli et al. [38] (4.0 kg CO_2/kg BD *vs.* 1.8 kg CO_2 eq/kg BD from RTFO). This discrepancy is attributed to emissions from land-use change. Clearly, the main challenge to improve the environmental performances of Argentinean soy biodiesel production stays in avoiding deforestation. The negative impacts are greatly reduced for soybean expansion on marginal and set-aside agricultural land. Environmental performances can further be improved by implementation of crop succession, soybean inoculation, reduced tillage and use of less toxic pesticides. The energy balance of soy biodiesel can also be improved by using (bio) ethanol in the transesterification process.

Avoiding deforestation and allocating the future land expansion to set-aside and marginal arable land significantly decreases the environmental performances of the system: (i) a reduction of 61% in GWP by avoidance of CO_2 emissions from soil and biomass; (ii) a decrease of 51% in CED as biomass energy use from primary forest is avoided; (iii) a reduction in AP by 12% as NH_3, N_2O and SO_2 emissions are avoided; (iv) a decrease in HTP by 57% as benzene emissions are avoided; and (v) a reduction in EP of 5% for avoided NH_3 and N_2O emissions during land provision. Other land-use changes than deforestation for soybean cultivation have occurred, such as conversion of other cropland (wheat, corn, sunflower or sorghum) and pasture land [131]. A default value of 0.05 kg CO_2 eq/kg BD is given by RTFO for grassland conversion [130].

Compared with the fossil reference, the specific Argentinean pathway to biodiesel (including deforestation) shows worse performance in all the impact categories with the exception of energy consumption. Significant influences in the environmental impact are land-use changes, BNF and use of fertilisers and pesticides, the soybean production method, use of alcohol, and the transport system. Expanding the system to account for crops succession will help to better model the system inputs in the agricultural phase. Although the position of Argentina as a soybean-based biodiesel exporter is cost-competitive it is not competitive from the environmental point of view unless certain actions are undertaken: avoiding deforestation, applying reduced tillage and crops succession, applying soybean inoculation methods, increasing yield, using low-toxicity pesticides and using biomass-based alcohols in FAME production. The improvements are necessary to comply with international sustainability criteria for biofuels production. Further considerations should be made to account for indirect land-use changes attributable to soybean cultivation. In a recent study Castanheira et al. [63] have assessed the effects of various direct land-use changes (DLUCs) on the GHG balance of soybeans produced in Argentina and Brazil and exported to Portugal, *cf.* Section 5.3.2.

In recent years there has been increasing focus on how production of soybean and its derivates (meal, oil, biodiesel) affects the environment. While most LCAs of vegetable oils, meal or biodiesel use mass or economic allocation (attributional LCA), Dalgaard et al. [41] have evaluated the environmental consequences of soybean meal consumption (production in Argentina and transportation to Rotterdam) using a system expansion (consequential LCA) approach according to ISO 14044 (2006) [132]. In the consequential LCA method co-product allocation is avoided through system expansion. System expansion implies that the inputs and outputs are associated entirely to soybean meal, and the product system is expanded to include the avoided production of palm oil and/or rapeseed oil. Table 15 lists the resource use for cultivation of soybean (Argentina, no deforestation), in comparison to rapeseed (Denmark).

Soybean meal is an important protein input to livestock and fish production. An increased demand for soybean meal implies an increased production of soybean oil as both commodities originate from soybean. Soybean meal consumed in the EU (33.2 Mt, 2010/2011) is primarily milled outside the EU. Argentina is the largest global exporter of soybean cake. Dalgaard et al. [41] did not consider deforestation for soybean production (and consequently emissions from land-use change) and no N fertiliser use (*cf.* Table 15). However, BNF values were higher (132 kg N/ha) than Panichelli's (70 kg N/ha) [38]. Dominating environmental impact categories are global warming, eutrophication and acidification. GWP of Argentinean soybean are reported as 0.64 kg CO_2 eq/kg [41] and 1.6 kg CO_2 eq/kg soybean [38], which is on account of different assumptions in the LCA inventory and in allocation (system expansion *vs.* economic allocation). Global warming in relation to soybean cultivation is dominated by N_2O emissions from degradation of crop residues (*e.g.* straw) and during the biological nitrogen fixation (BNF). Eutrophication is not a major problem in soybean cultivation [41]. Acidification values for soybean were 5 and 0.8 g SO_2 eq/kg soybean in Refs. [38] and [41], respectively. The acidification potential (AP) is very sensitive to the increased transport distance by truck. The results show that soybean meal consumption in Europe has an impact on the global environmental (*e.g.* global warming) and on the local environment outside Europe (*e.g.* acidification, land use).

Table 15
Resource use for cultivation of 1 ha of soybean and rapeseed.

Resource	Soybean (Argentina)	Rapeseed (Denmark)
Fertiliser (N) (kg)	0	167
Fertiliser (P) (kg)	16	24
Fertiliser (K) (kg)	0	77
Diesel (L)	42	125
Lubrificant oil (L)	4	13
Electricity (natural gas) (kW h)	8	23

After Ref. [41].

4.4. Chinese soy biodiesel

Ou et al. [21] have compared WTW fossil energy consumption (FEC) and GHG emissions of soy biodiesel (SB), jatropha biodiesel (JB) and used cooking oil (UCO)-derived biodiesel (UB) in China. Net energy value (NEV) and net energy rate (NER) were used to assess the energy saving effect of biodiesel pathways: NEV is the energy contained in the fuel minus its life-cycle primary consumption (E_{LCA}); NER is the ratio of the energy contained in the fuel to the LCA fossil fuel consumption. The SB biodiesel pathway has a slightly negative NEV, whereas the JB and UB pathways have positive NEVs. The NER efficiencies are 0.981, 1.461 and 2.004 for SB, UB and JB, respectively.

China's current biodiesel pathways are geographically unique and differ in energy consumption (EC) and GHG results in LCAs for other regions (USA, EU, Brazil, *etc.*) by: (i) China's coal-dominant energy mix; (ii) use of high fertiliser application rates for agricultural practices in Chinese farming (Table 16); and (iii) PRC's relatively higher energy consumption in the industrial biodiesel processes. Whereas both non-food feedstock pathways (JB and UB) are lower in EC and GHG emissions levels than conventional petroleum diesel (PD), SB is higher in EC and GHG emissions (WTW: 110.5 g CO_2 eq/MJ). However, in PRC conditions, petroleum consumption in all biodiesel pathways can be reduced through increased coal consumption. As a result, all three alternative

Table 16
Basic parameters for the soybean biodiesel pathway in China.

Soybean yield (t/ha)	1.8
Cultivation energy (MJ/ha)[a]	4494
N fertilisers (kg/ha)	88
P fertilisers (kg/ha)	33
K fertilisers (kg/ha)	27
Pesticides (kg/ha)	4
Collection radius (km)	200
Conversion rate (t feedstock/t fuel)	5.9
Energy for extraction (GJ/t)[b]	12.9
Transportation for distribution (km)	200
Allocation of by-product (%)	27.5

After Ref. [21].

[a] Energy mix: gasoline 7.33%, diesel 88.87%, electricity 3.80%.
[b] Energy mix: coal 90%, electricity 10%.

biodiesel pathways are feasible in PRC due to the local rich coal/poor petroleum scenario [133].

Energy balance and GHG emission levels for soy biodiesel in China are quite different from those for North and South American producers with higher soybean yields (2.80 t/ha as compared to 1.7 t/ha in PRC). In Chinese conditions, soybean crop production accounts for the largest share of 59% in the total energy cost (including 15% feedstock transportation) and industrial conversion 41%. Fertilisers make up almost 40% of the energy cost of the agricultural crop production stage, due to heavy usage (148 kg/ha; *cf.* 44 kg/ha in USA [46]) and high embodied energy intensities. In PRC 50% of N fertiliser is derived from coal feedstock. Pesticide input and energy for transportation are also important factors for high energy consumption in the agricultural stage (Table 16). As shown in Table 17, soy biodiesel shows high GHG emissions in the feedstock stage (73.9 g CO_2 eq/MJ or 67% of total pathway). The GHG level is very high due to the fertiliser's N_2O emissions and the dominant power role of coal during this process step. When 1 MJ of fuel is obtained and utilised (*i.e.* including use phase emissions of the vehicle), JB and UB indicate significant GHG reductions of 50.4% and 21.5%, respectively, with respect to petrodiesel. On the contrary, SB leads to an increase of 7.7% (Table 17).

A comparison of EC and GHG emission results of LCA studies in PRC conditions shows considerable differences in NER and NGRR (net GHG reduction rate) values. These differences are on account of: (i) China's N fertiliser production, including feedstock source, transportation modes, and process energy consumption; (ii) N_2O emissions in N fertiliser applications; and (iii) CO_2 and CH_4 emissions associated with China's coal mining, crude oil and natural gas (NG) exploration stages [21,134]. Taking these considerations into account leads to a rather pessimistic result for Chinese soy biodiesel.

Feedstock productivity levels must be increased, and there must be a reduction in fertiliser utilisation and energy consumption during the cultivation and transportation stages in order to achieve the goals of energy balance and GHG emission reduction. The following actions are recommended: (i) higher productivity through seed selection and genetic engineering; (ii) reduction of EC and GWG in the agricultural stage through careful selection of planting sites, reduced irrigation and reduced and more timely fertiliser usage; (iii) reduction in EC and GWG transportation of feedstocks and fuel through a more rational arrangement of fuel and biodiesel production sites, (iv) reduction in EC during the crushing and extraction process through promotion of high-performance low-EC refining equipment; and (v) higher energy efficiencies through optimising by-product output [21].

Hou et al. [78] have compared LCA of biodiesel from soybean, jatropha and microalgae in Chinese conditions. For the soybean and jatropha agriculture process reference was made to Ou et al. [21]; industrial-scale facilities for biodiesel production from microalgae have not yet been built. Life cycles of these three biodiesel products consume less fossil resources as compared to fossil diesel, and produce less GHG emissions. Better environmental performance is registered for abiotic depletion potential (ADP), global warming potential (GWP) and ozone depletion potential (ODP) but impacts are worse in seven other environmental categories. The life-cycle ADP of soybean, jatropha and microalgae-based biodiesel decreases by 70.0%, 82.3% and 80.9%, respectively, compared with fossil diesel, and GWP decreases by 61.7%, 80.3% and 82.2%, respectively. The primary reasons for this significant decrease are the large amounts of solar energy and CO_2 uptake in biomass growth. The reduction of dependency on fossil fuels in biodiesel production leads to a better performance on ozone depletion potential (ODP). Emissions from crude oil extraction and refining are avoided.

The higher eutrophication and acidification potentials (EP and AP, respectively) of biodiesel are mainly caused by upstream emissions of nitrate and phosphate leaching to groundwater, and NH_3 and NO_X to air from fertiliser application. The agricultural phase contributes 68.0%, 45.5% and 34.0% to the life-cycle EP of soybean, jatropha and microalgae-based biodiesel, respectively. Freshwater aquatic ecotoxicity potential (FAETP) contributes 91.0%, 91.9% and 44.0% to the total environmental impact in the life cycle of soybean, jatropha and microalgae-based biodiesel, respectively. Agriculture is also the main contributor to the terrestrial ecotoxicity potential (TETP) of soybean and jatropha biodiesel due to the use of agrochemicals. Human toxicity (HTP) and marine aquatic ecotoxicity potential (MAETP) in the life cycle of biodiesel are largely contributed by processes of chemicals, steam and electricity production. Use of coal for electricity production in China, with seven heavy metal and HF discharges causes significant impacts. The level of photochemical oxidation potential (POCP) caused by producing and using biodiesel fuels is mainly on account of hexane emission during vegetable oil extraction, which contributes 25% to 30% to the life-cycle POCP of the vegetable oil-based biodiesel. Not unexpectedly, an increase in transport distances (from 20% to 80%) makes environmental performance worse in most impact categories, notably ADP, ODP and GWP due to CO_2 emissions and depletion of fossil resources.

Other critical impacts in biodiesel LCA studies are water and land use (not included in this study). It is well known that land-use change can originate in large amounts of GHG emissions from soils [4,38,135,136]. Such GHG emissions might largely exceed the annual GHG reductions that biofuels would provide by displacing fossil fuels.

The choice of the allocation method, transport distance, uncertainty in jatropha and microalgae yield and oil content, and recycling rate of harvest water of microalgae significantly influence LCA performance of biodiesel. Careful management of biomass agriculture and development of biodiesel production technologies, improvements in the energy structure and promotion of energy efficiency in China are considered as key measures to lower the environmental impacts in the life cycle of biodiesel production and use in the future.

Table 17
GHG emissions of biodiesel pathways.[a]

Pathway (unit)	SB (g)	SB (%)	JB (g)	JB (%)	UB (g)	UB (%)	PD (g)	PD (%)
Feedstock stage	73.89	67	24.61	47	34.40	46	56.84	55
Plantation energy	16.91	15	1.57	3				
Fertiliser input	42.27	38	18.06	35				
Pesticide input	5.85	5	0	0				
Feedstock transportation	8.87	8	5.03	10	34.40	46		
Fuel stage	36.39	33	27.36	53	40.39	54	45.76	45
Total	110.50	100	51.97	100	74.75	100	102.60	100

After Ref. [21].

[a] g CO_2/MJ biodiesel obtained and utilised.

Jatropha and microalgae are more environmentally competitive biodiesel feedstocks than soybean in terms of all impacts. This is largely a result of the lower level of agricultural inputs per unit of oil output than soybean. In particular, microalgae-based biodiesel shows very low impacts for FAETP and TETP on account of the absence of toxic agrochemicals in microalgae cultivation. However, microalgae cultivation consumes more electricity in comparison to jatropha, which increases ADP by 8%. Biomass yield and lipid content are highly uncertain parameters in jatropha and microalgae agriculture, varying with land suitability, tree age, microalgae species, solar radiation, temperature, *etc.* Dry seed yields of jatropha typically range between 1500 and 5000 kg/ha and seed oil content between 25% and 47%. Algal growth rates range between 5 and 50 g/m^2 d, and lipid content between 15% and 80%. Larger impacts are generated for feedstock with lower biomass yield and lipid content. Given that growth rate and lipid content conflict with each other, a trade-off must be found between growth rate and lipid content when choosing the suitable microalgae species for producing biodiesel.

Hu et al. [49] have reported a well-to-wheels (WTW) life-cycle energy, environmental and economic assessment of soy biodiesel (SB) as an alternative automotive fuel in China assuming a plant size of 10 kt/yr and using mass allocation. Compared with conventional diesel (CD), SB has similar well-to-pump (WTP) total energy consumption (1.261 and 1.307 MJ/MJ, respectively), 76% lower WTP fossil energy consumption (0.306 MJ/MJ for SB *vs* 1.256 MJ/MJ for CD), with higher WTW emissions for NO_X (79%) and lower WTW emissions for HC (31%), CO (44%), PM (36%), SO_X (29%) and CO_2 (67%). Crude oil extraction and refining are the key stages for CD responsible for total energy and fossil energy consumption, accounting for 82% and 15% of the WTP total energy consumption, and 83% and 15% of the WTP fossil energy consumption, respectively. Soybean cultivation and biodiesel conversion (data not detailed) are the main stages responsible for fossil energy consumption, accounting for 55% and 31% of the WTP fossil energy consumption, respectively. Therefore, WTP fossil energy consumption for SB production can effectively be reduced by: (i) more advanced manufacturing technology which requires less energy to produce fertilisers; (ii) more advanced soybean cultivation technology (less use of fertilisers); and (iii) more advanced biodiesel conversion technology (with higher energy efficiencies in the conversion process) [49].

Soybean biodiesel is more environmentally friendly than conventional diesel. Soybean cultivation, biodiesel conversion and combustion are the three main stages responsible for PM emissions. Soy biodiesel combustion is the key stage responsible for HC, CO and NO_X emissions. Soybean cultivation and biodiesel conversion are the two main stages responsible for SO_X and CO_2 emissions. SO_X emission at the biodiesel use stage is almost zero because of the very low sulphur content of SB. CO_2 emission at the biodiesel use stage is zero because the carbon in SB is absorbed from the atmosphere via photosynthesis during soybean cultivation. Soy biodiesel is a promising clean and alternative fuel. It is generally agreed that compared with CD, biodiesel has better degradation characteristics and lower hydrocarbon (HC), particulate matter (PM), CO_X and SO_X emissions, but higher nitrogen oxides (NO_X) emissions [29].

China is experiencing increasing pressure from other countries on global warming issues. More advanced engine and tail gas treatment technology would be effective to reduce pollutants and CO_2 emissions during the CD life cycle. This technology would also be effective to reduce the HC, CO, NO_X and PM emissions during the SB life cycle, while adopting more advanced soybean cultivation and biodiesel conversion technology would be effective to reduce the PM, SO_X and CO_2 emissions [49]. There are several ways of reducing NO_X emissions from soybean fuelled engines such as more advanced fuel injection timing and a special NO_X amendment additive [137].

As to life-cycle cost, feedstock cost is greatly affecting the cost of SB at the biodiesel plant gateway. Soy biodiesel needs government subsidy to assure price competitiveness against CD in the near future. At present, China has to import large amounts of soybean to meet its non-fuel demands (58 Mt in 2011/2012). Soybean is one of the important oilcrops for edible oil production in China. At a B5 mandate for motor vehicles about 57% of the Chinese soybean oil production (11 Mt in 2011/2012) would be needed as a feedstock to produce 6.3 Mt of soy biodiesel. As China would have to import large additional amounts of soybean to meet soydiesel demand, it is currently not considered to be the best option for the country [49]. China requires higher yield soybean species as well as better fertiliser management before domestic soy biodiesel becomes a sustainable biofuel. Other kinds of alternative fuels to substitute conventional diesel have priority. It is strategically more important for China to diversify its biodiesel feedstock (*Jatropha curcas, Cornus wilsoniana*, rapeseed).

4.5. European soy biodiesel

European interest in soy biodiesel production is limited, as reflected in few LCAs. Venturi et al. [22] have compared the energy inputs and outputs of three energy crop chains (rapeseed, sunflower and soybean) in European agricultural systems. The comparison shows considerable margin for improvement in many areas with low yields. The main output data for soybean and soybean oil denote a wide regional variability. Grain energy outputs are extremely variable, with values around 15 GJ/ha in less favourable conditions up to about 75 GJ/ha. If oil output is considered without including by-products, soybean shows low values because it has double the amount of protein and half the oil. Crop input data also vary considerably, notably tillage (6.5–13.6 GJ/ha) and fertilisation (1.9–12.0 GJ/ha). Table 18 shows a breakdown of field inputs, where the most relevant contributors are fuel and fertilisers.

Table 18
Field phase inputs for soybean cultivation.

Fuel[a]		Fertilisers[b]		Pesticides[c]		Others[d]		Total
(GJ/ha)	(%)	(GJ/ha)	(%)	(GJ/ha)	(%)	(GJ/ha)	(%)	(GJ/ha)
10–16.1	66.7–46.0	0–10.7	0–30.6	0.8–2.2	5.3–6.3	3.2–6.0	21.3–17.1	15–35[e]

After Ref. [22].

[a] 47.8 MJ/kg.
[b] 76, 14 and 10 MJ/kg for N (urea), P_2O_5 and K_2O, respectively.
[c] Average of applied pesticides and doses.
[d] Seeds, machineries, etc.
[e] Heavy soils.

Fuel is particularly high in heavy soil conditions. Inputs have a smaller range of variation compared to output with a factor of about 2 between minimum and maximum. Post-harvest inputs (*cf.* 2.13 and 4.21 GJ/ha for soybean and rapeseed, respectively [138]) are directly correlated to processed product amount (*cf.* also Fig. 3 [42]).

The energy balance (both in terms of net gain and ratio) is not always favourable for soybean. The balance even gets worse for its methyl esters, both with and without allocation for co-products. Crop input can be diminished by reduction or by rationalisation of technical tools. Use of high capacity machines, which achieve considerable reduction of time per unit area, may reduce crop input while maintaining high yields. Although energy gains are possible by technical rationalisation, this does not guarantee a positive economic result. It is advisable to operate in such a way that output is significantly higher than 15–20 GJ/ha for soybean, while adopting technical means to reduce input costs without significantly affecting yield.

Various LCAs have evaluated the impact of soy biodiesel produced overseas (USA, Brazil and Argentina) and utilised in Switzerland [38,82], *cf.* Sections 4.3 and 5.2.3.

Morais et al. [62] have compared soy biodiesel and liquefied petroleum gas (LPG) as automotive fuels in Portugal using LCA for twelve impact categories and economic allocation. Climate and soil in Portugal are unsuitable for soybean cultivation. Soybean biodiesel (SB) is produced in Portugal from soybean imported from Brazil or USA. Inventory data for the SB life cycle were taken from literature and databases. A Western European or Portuguese energy mix was used in modelling. Process average data of Sheehan et al. [29] were used. For the assessment of the potential environmental impacts (PEIs) various characterisation models were used, as proposed by Pennington et al. [74]. Normalised PEI categories were aggregated in one total PEI indicator. LPG production accounts for 93% of the normalised total PEI of the life cycle. The total environmental impact of LPG is 2.54 times higher than that of soy biodiesel. Agriculture and transesterification account for 50% of the total normalised PEI in the SB life cycle. In comparison to LPG, SB contributes 45% and 79% lower global warming and abiotic resources depletion. In particular, marine aquatic ecotoxicity and human toxicity are much lower for biodiesel. Contributions of SB to acidification (AP), terrestrial eutrophication (TE) and land use (LUC) are higher than for LPG, namely by 47%, 58% and 85%, respectively. For soy biodiesel acidification due to NO_X and SO_X emissions during steam production is the most significant impact category. Land-use impacts (due to occupation and transformation) account for 76% of PEI in the soybean agricultural stage. Effects of deforestation and biodiversity loss were not quantified due to lack of data. A comprehensive evaluation of the preferable fuel to be used in the Portuguese context should complement LCA results with socio-economic considerations.

In an LCA comparison of biodiesel from soybean, rapeseed and sunflower oil the origin of the data and the georeference (presumably Spain) were not made clear, consequently, only generic conclusions can be derived [77]. In order to reduce the environmental impact of biodiesel the main attention should be focused on the agricultural oilcrop production stage. In terms of land use (and consequent agrochemicals application) soybean and rapeseed cultivation is to be preferred over sunflower for biodiesel production.

5. Discussion

A valuable substitute for fossil fuels should provide a net energy gain over the energy source used to produce it, be sustainable, have superior environmental benefits over the fossil fuel it displaces, be economically competitive and producible in large quantities without reducing food supplies [20]. Common metrics used to compare alternative bioenergy pathways describe energetic performance (energy ratio), environmental performance (emissions, land and water use), economic performance (cost), and social and ecological performance (human welfare, biodiversity) [139]. The choice of production system and scale should minimise the total environmental load.

Both EU's RED and FQD define more environmental than sustainability criteria. The Fuel Quality Directive aims at promoting the cleanest fuels and obliges suppliers to reduce the life-cycle GHG intensity of transport fuel by 6% by 2020 compared with 2010 [14]. Reduction of emissions can be achieved in various ways. The LCAs of Section 4 for soy biodiesel give clear evidence and suggest numerous opportunities to enhance the efficiency of both the agricultural and processing technologies.

LCA results make difficult comparison. Biodiesel production facilities of different nameplate capacity are sourcing different feedstocks and use different methods of modern manufacture. Life-cycle assessments may report apparently inconsistent results, originating from: (i) incomplete or outdated data; (ii) process simulation software; and/or (iii) lack of full comprehension of the complexity of the energy system requirements. More recent research tools allow for more correct full life-cycle analyses.

Various sensitivity analysis have determined the influence of the variations in assumptions, method choices, and process data on the results [20,38,44,47]. Significantly different results can be obtained depending on the detail of the input data and the assumptions made to build up the LCA inventory. Disagreement on LCA results is eventually attributable to differing data sets (including data sources and ages) and methodologies. Methodological differences include choices of the system boundaries, functional units, allocation procedures and other assumptions.

5.1. Agricultural phase

Growing crops for energy involves using land in a different way. Land availability is declining. Arable land for soybeans – in competition with other crops – is limited and yield improvements are restricted. Land requirement for biodiesel production varies considerably for different oilseeds due to different yields and oil content. Table 19 summarises typical values of oil productivity for the most common crops. Various important aspects of agricultural practice are tillage systems, crop rotations *vs.* monocultures and land-use (change). The tillage system (conventional or reduced) alters energy inputs for machinery and manufacture, enables the use of short-cycle soybean varieties, and affects herbicide inputs. The European model of farming with frequent ploughing and high fertiliser inputs is often completely inappropriate for many tropical regions [140]. On a global basis increased demand for food and feed will continue to be responsible for a greater proportion of

Table 19
Typical values of oil productivities for different crops (litres of biodiesel/hectare).

Feedstock	Oil productivity
Palm oil	5780
Babassu palm	1780
Castor bean	1370
Rapeseed	1150/1200[a]
Sunflower seed	970
Soybean	430/700[b]
Cottonseed	310

[a] Biodiesel production from rapeseed in Europe [13].
[b] Biodiesel production from soybean in Brazil [13].

land-use change than the additional demand for biodiesel. Demand for agricultural land is one of the most significant drivers for deforestation.

Production intensity in agricultural cropping is related to the demand for energy. Generally, fertilisers production has the highest energy demand and also carries the highest environmental impacts, but this is low for soybean in comparison to other oilcrops, typically 4.7 kg N/ha/yr in US conditions (Table 8); *cf.* 81 kg N/ha/yr for a low-nitrogen cultivation of rapeseed [111]. Chinese soybean agriculture suffers from an overdose of fertiliser use (88 kg N/ha) (*cf.* Table 16). A further disadvantage of high N applications is that excessive or badly timed additions may result in leaching of excess mineral N into water reserves with resulting risks of NO_3^--N pollution of drinking water and contributes to eutrophication of rivers and lakes. Tropical agriculture also uses some pesticides which are forbidden in Europe in view of their toxicity.

Kägi et al. [83] have compared organic farming (without fertilisers and pesticides) to integrated production (IP) [141] (with > 75% mineral N fertilisers) using SALCA methodology (Swiss Agricultural Life Cycle Assessment). Yields of 2497 kg/ha (bio) and 2610 kg/ha (IP) were reported. Organic farming uses less energy and pesticides but generates higher nutrient emissions than integrated farming. Biodiversity was evaluated more positively for organic farming. For soybean cultivation organic farming is a valid alternative to IP, requires fewer resources and improves soil quality.

The water requirements of soy biodiesel production depend on geographic and climatic variables. Evapotranspiration requirements for soybean crops in the United States are about 4200 L water/L ethanol eq (Le) [142]. The water requirements to produce an equivalent amount of energy from biofuels are much larger than for traditional sources (*cf.* soybean biodiesel irrigation 13.9–27.9 ML/MWh to petroleum extraction 10–40 L/MWh) [68]. The overall water footprint associated with biofuels not only comprises water consumption but also water quality. Agricultural activity (tilling, agrochemicals application) have some inevitable adverse impacts ranging from local groundwater pollution by fertilisers and pesticides to eutrophication of both inland waters and distant coastal waters. Annual crops such as soybeans are prone to cause soil erosion and nutrient runoff to surface waters. Use of marginal lands pressed into agricultural service requires higher agrochemicals application, is more susceptible to erosion and runoff, and increases impacts on water quality.

The main stages in the agricultural phase are cultivation and crushing (oil extraction). Extraction consists of solvent treatment using hexane. Modern soybean crushing facilities are far more energy efficient than in the past with an increase in US industry average oil extraction rate of 13% between 1990 and 2007 (*cf.* Table 4). Hexane losses have been limited (US EPA). The energy required for US soybean crushing has decreased from 2.6 to 1.1 MJ/L of biodiesel. The modern crushing facilities in Argentina are at top level. The vegetable oil extraction efficiency in small-scale systems is lower in comparison to large-scale systems [143]. Before transesterification additional energy consuming oil refining is required. There are considerable differences between estimates of the primary energy inputs and CO_2 outputs of soybean crushing/extraction/refining. These are on account of scale, extraction efficiencies and allocation (credits). Total fossil energy use for soybean crushing typically amounts to 7.34 MJ/kg BD (Table 3). The relative importance in terms of energy requirements and environmental impacts of the various stages in soy biodiesel production may be seen from Fig. 3 [42] and Tables 2, 3 and 10 for various agricultural conditions. In US conditions cultivation and crushing both account for about 33% of the total energetic impacts [50]. Soybean is not an energy efficient crop that requires a high energy input to produce 1 t of oil, and consequently of biodiesel. The energy output of soybean is over 3.5 times lower compared to oil palm.

The main problems in soybean cultivation stay with land use and agrochemicals. Other problems facing soybean production are weed resistance, rundown soils and rising costs [144]. In some regions (Argentina, Brazil) temporary reductions in yield have been caused by a foliar disease (Asian soybean rust) [145].

5.1.1. Energy conservation in agriculture

Effective use of energy in agriculture is important for sustainable agricultural production to optimise economic return, preserve fossil fuel reserves and reduce air pollution [146]. Detailed knowledge of fossil fuel energy use in agricultural systems in essential in developing cropping practices that utilise limited energy resources more efficiently.

Energy analysis provides important information on cropping system properties. There is no standardised methodology for determining the optimum level of energy input per area of agricultural land or unit output. To determine the energy efficiency in crop production, different energetic parameters are available, such as energy balance or energy gain (net energy output), energy intensity and output/input ratio (EROI). A maximum energy gain is desirable when land is used to produce renewable energy or when land area for growing crops is limited. Energy intensity and output/input ratio are measures of the environmental effects associated with crop products. Therefore, these parameters can be used to determine the optimum intensity of land and crop management from an ecological point of view. Energy indicators depict the efficiency of production systems, allow comparison of different production intensities and are a suitable supplement to economic analysis [147].

The agricultural phase in biodiesel production is usually the most energy intensive (*e.g.* for rape biodiesel [16]). Although sunlight energy is the primary input to crop production, energy balance sheets in agriculture are mainly determined by the support energy (fossil energy inputs of mineral fertiliser and fuel), which are highly correlated to the production intensity. Fertilisers application rates depend on oilcrop and location. Nitrogen is the most limiting nutrient for crop farming [148] and optimum N management is the most important factor for energy conservation. Adjustments in the use of fertilisers, fossil fuels, organic fertiliser, herbicides and biological control of pests decrease the energy consumption in the agricultural stage.

Soybeans can be produced without or with nearly zero nitrogen (Table 14), which makes them advantageous for the production of biodiesel. Nitrogen fertiliser is one of the most energy costly inputs in crop production. Soybean is one of the few oilseed crops that acquire nitrogen through biological nitrogen fixation (BNF). This favours its production energetics. Yet, the energy balance (EROI) for soybean (2.50) is the least favourable in comparison to rapeseed (3.05) and oil palm (9.60). Oil palm is a highly energy efficient crop. Oil palm cultivation and processing requires lower inputs of agrochemicals (pesticides), fertilisers and fossil fuels to produce 1 t of oil, with fewer resulting pollutions and emissions [149].

Apart from fertilisers, the direct energy input due to fossil diesel consumption is the second most important input factor ranging from to 6.18 MJ/L [20] to 5.50 MJ/kg BD [37] or about 34%. The energy required to grow crops depends on the tillage system. At low N rates, diesel contributes a greater percentage of total energy input. In contrast to fertiliser and diesel, the factors seed material, plant protection and machines are less important. Although pesticide manufacturing tends to be energy intensive, the contribution to the total energy input is small (< 10%) because

of the generally low application rates per unit land area (more important in China, Brazil and Argentina than for USA).

The energy balance is mostly favourable for soybean oil (Table 13) but less so for its methyl ester (Tables 3 and 7) [22]. In various conditions only low positive or even net negative energy returns have been reported for the soybean agricultural stage, *e.g.* USA [84], Argentina [38], China [21], and occasionally in Europe [22]. If we disregard Pimentel's results [84] for the reasons given (Section 4.1), then the US agricultural energy balance for soy is largely positive and the best worldwide [46,50,51].

The critical effect of increased yield (from 2293 kg/ha (1990) to 2555 kg/ha (2002) and 2885 kg/ha (2006)) on primary energy is illustrated for the US soy biodiesel pathway with fossil energy ratios (FERs) increasing from 3.2 (1990) [29] to 4.56 (2002) [37] and 5.54 (2006) [50]. The low cumulative energy demand in US soybean cultivation derives from various factors: high crop yields (2641 kg/ha *vs* 2544 kg/ha in South America), no deforestation, highly efficient logistics, relatively short transport distances, and restrained use of pesticides and other agrochemicals. Implementation of Roundup Ready (RR) soybeans, resulting in improvements in soybean weed management, permits low-till practices (on 45% of soybean cultivated area in 2006), thereby reducing soil erosion and energy expenditure.

Table 20 compares agrochemical input data for soybean production in the main crop producing regions. As illustrated for the Argentinean soybean complex, extensive adoption of no-till cropping (88% of total soybean cultivation), modern and efficient industries, and short distances from farms to crushing, refining and port facilities reduce both energy requirements and GHG emissions. Fertiliser and pesticide use in soybean cultivation in Argentina [38,150] are lower than in Brazil [79]. Taking into account land-use issues (deforestation) Panichelli et al. [38] have described an overall high energy consuming biodiesel pathway for Argentina, yet still below the fossil reference CED value. Chinese agriculture suffers from low soybean yields, low energy efficiency and high fertiliser use [21].

5.1.2. Environmental performance

One of the most widely used metrics for comparing environmental performance of bioenergy pathways is the GHG emissions (or equivalents) per unit energy (kg CO_2 eq/GJ). This metrics allows measuring the whole system performance but is less straightforward for systems producing both energy and non-energy products, as in case of soy biodiesel. In practice, the amount of GHG saved is not limited by the amount of fossil fuels replaced but by the amount of land available [152].

Table 20
Comparison of typical yield (kg/ha) and agrochemical input data (per 1 t oilseeds) of soybean production worldwide.

Process value	Unit	USA [46]	Argentina [38]	China [21]	EU RED	Ecoinvent [151]
Yield	kg/ha	2766	2591	1800	2798	2641
N fertiliser	kg/t	1.60	1.93[a]	48.9	2.65	1.89
BNF	kg/t	–	27.0	n.a.	–	n.a.
P fertiliser	kg/t	5.00	4.05	18.3	23.6	6.12
K fertiliser	kg/t	9.30	–	15	22.15	9.33
Quick lime	kg/t	94.00	–	–	–	8.35
Pesticide	kg/t	0.52	0.9[b]	2.2	0.96	0.47
Energy consumption	MJ/t	763	4022[c]	3770	750	752

n.a., not available.
[a] First-class soybean production only.
[b] Expressed in grams of active compound (glyphosate).
[c] Including land provision through deforestation.

A main argument for the production and use of SME as a biofuel is its potential to reduce the emissions that contribute to global warming and one of the main objectives of the establishment of energetic crops in the EU is the fulfilment of commitments to the reduction of greenhouse gases [153]. Biodiesel production is not entirely climate neutral. Cooling due to fossil fuel savings (reduced release of CO_2) is greatly offset by global warming by considering GHG emissions from agriculture. Direct GHG emissions from cultivation arise from fertiliser application and BNF together with diesel combustion from agricultural machinery. Indirect GHG emissions are on account of fertilisers, agrochemicals (pesticides, *etc.*), limestone, diesel and electricity. In almost all reported pathways the most significant contributions to GWP from soybean oil as a feedstock for biodiesel come from soybean cultivation but the US and Argentinean cases show that this can be different. In the most favourable case (no land-use effects, modern agriculture) the net energy value of SME amounts to 26.8 MJ/L and SME saves 56% of GHG emissions as compared to petrodiesel [50,154]. The cumulated non-renewable energy demand (CED) correlates with the GHG emissions. Carbon dioxide comes from production of fertiliser, traction and from transportation of agricultural inputs and outputs. Irrigation, which has a positive impact on crop yield, has a negative effect on the energy consumption and N_2O emissions. The relevant emissions contributing to GWP by soybean cultivation in Brazil are 61% N_2O, 37% CO_2 and 2% other (including NH_3 and CH_4) [155].

Key uncertainties as to global warming derive from the effects of climate-active species (also including NO_X, CO, SO_X, aerosols), poorly characterised emissions from agriculture (in particular N_2O), soil carbon sequestration and allocation methods. Soil carbon sequestration *cq.* release is highly site specific, dependent on soil type, prior land-use application, and agricultural practice.

Biodiesel production has multiple environmental impacts. Chief among these is land-use change, which also greatly influences the extent to which biofuels contribute to the mitigation of GHG emissions. Other environmental impacts concern water consumption, the use of fertilisers and pesticides. Large-scale biofuels production also has socio-economic impacts (not evaluated by LCAs). Water use efficiency of plants is an important parameter in evaluating agricultural productivity and planning water resource utilisation, especially in semi-arid and arid regions. Irrigation is a means of increasing agricultural productivity (at a cost). Brazil is naturally well endowed with 20% of global fresh water reserves. Water consumption (excluding evapotranspiration) is some three orders of magnitude higher for biodiesel than for fossil diesel [29].

If land-use change is not considered, land management practices are the most important determinant of GHG impacts. The dominant factors determining the environmental and biodiversity impacts of biofuels are the types of lands used for producing biofuel feedstock (forestland, cropland, marginal or degraded land) and the feedstock production practices employed, including the plant species cultivated [63,81]. The EU RED requires that biofuel feedstock must not be grown on land with high biodiversity value. Negative biodiversity impacts are high for soybean. Many of the potential environmental impacts are evitable and can be limited. Not cutting forests to generate arable land, but conserving soils so that they can be used productively for a much longer time would improve the environmental performance in Brazilian agriculture [118,119].

Using no-tillage practices instead of mechanical tillage, use of cover crops and maximising the return of harvest residues to arable soils leads to higher soil carbon stocks and this lowers life-cycle CO_2 emissions of biofuels [117]. Fig. 4 shows total average CO_2 emissions from agricultural inputs (seeds, fertilisers, pesticides, *etc.*) and agricultural machinery for soybean using three

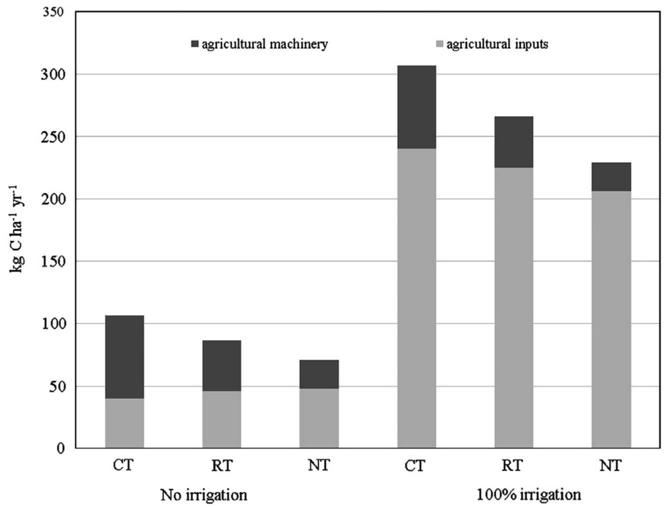

Fig. 4. Total average CO_2 emissions from US soybean cropping using three different tillage practices (CT, conventional tillage; RT, reduced tillage; NT, no-till), with and without irrigation. After Ref. [156].

different tillage practices (CT, RT and NT) in different conditions of irrigation [156]. Based on 1995 US average crop inputs for soybean, no-till without irrigation emits less CO_2 from agricultural operations than RT and CT, with 71, 87 and 107 kg C/ha yr, respectively (Fig. 4). It has been assumed that the change in tillage practice does not affect the level of productivity. Changes in tillage generally imply a change in the use of fossil fuels in agriculture. On average, a change from CT to NT will result in C sequestration in soil plus a savings in CO_2 emissions from energy use in agriculture. NT generally contributes less to the atmosphere than does CT. Without irrigation (on 95% of US soy area) an average continuous soybean crop produces less CO_2 emissions from crop inputs when using CT than when using NT (Fig. 4). However, if the crop is irrigated, the NT practice produces less CO_2 emissions. In a scenario with increased fossil-fuel use for cultivation (from agricultural machinery) part of the gain from sequestration of atmospheric C is negated by the increase in CO_2 emissions.

Agriculture and transport currently each account for about 14% of global annual human-caused GHG emissions (mainly CO_2, CH_4, and N_2O with relative IPCC emission coefficients of 1, 23 and 296 CO_2 eq). The main components of agricultural emissions outside of land-use change are N_2O and CH_4. Nitrous oxide comes from field emissions (denitrification and nitrification) and from production of N fertilisers. Carbon is released from both biomass and soil by conversion of forest, shrub, and grassland to cropland. Key issues effecting soil carbon exchange and thus the GHG balance of biodiesel are: (i) land use; (ii) geographic region (soil type and climate); (iii) soil management practices (full-, reduced or no-tillage); and (iv) carbon inputs to soils (return of crop residues to the field, manure carbon input cropping, *etc.*). A large degree of variability exists concerning the management practices and input levels. Development of agricultural systems needing low fossil energy inputs while maintaining high output helps to reduce agricultural CO_2 emissions [157].

Oilcrops are typically produced through intensive farming which is responsible for a large portion of the GHG emissions from these pathways. Apart from CO_2 other emission sources derive from nitrogen inputs to soil for crop farming: (i) application of mineral fertiliser or animal manure; (ii) biological nitrogen fixation (BNF); and (iii) crop residues (*i.e.* nitrogen in the aboveground biomass left in the field after harvest and in the belowground biomass-roots). In the United States, soil management activities, such as fertiliser application and other cropping practices, account for 67% of all N_2O emissions. Corn and soybean production systems are responsible for the highest N_2O emissions among major US croppings [158]. Direct and indirect N_2O emissions derive from 262.7 g N/bu for soybean and 561.6 g N/bu for corn farming [44]. Application of fertilisers is often almost negligible for soybean.

A source of nitrogen inputs to soil for crop farming includes waste biomass left in the fields after harvest. Under direct sowing, the residues are not buried but left on the field which reduces the amount of nitrous oxide released. For soybeans, nitrogen in the above- and belowground biomass is eventually from nitrogen fertilisers and the BNF process. High soil mineral N levels are transient, because what is not taken up by the crop or immobilised in the organic matter is quickly lost by (de)nitrification processes and volatilisation as NH_3 and/or N_2O from the soil to the air (direct emissions) and by leaching of nitrates into water streams (indirect emissions), and therefore cropping systems require continuous or regular additions of nitrogen. Both timing and method of application are important.

Biological nitrogen fixation, which depends on the N content in the grain, the type of soil and the agricultural practices, provides an important input of nitrogen for soybeans. For Argentina, BNF varies between 80 and 120 kg N/ha, and reduced tillage systems allow fixing more N than conventional tillage systems [38]. Other BNF values reported are 132 kg N/ha for Argentina [41] and 170 kg N/ha for Brazil [115]. BNF crops such as soybean cause direct N_2O emissions. The release of N_2O from soils is caused by microbial activity. The emission depends on various factors which are not well understood [159]. Tillage affects the conditions for N_2O and NO emission from soils. Some studies have observed higher N_2O losses for no-tillage systems compared to conventional tillage [160]. However, N_2O losses from no-tillage systems may also be lower than from tilled soils where fields have remained uncultivated for a number of years.

Nitrous oxide (N_2O), a potent GHG, is produced from nitrogen in the soil through bacterial processes of nitrification and denitrification (direct N_2O emissions). In certain conditions, soybean root nodules can secrete excess ammonium into the soil, which can be charged into the atmosphere as N_2O via (de) nitrification. N_2O can also be produced indirectly through leaching and runoff of nitrate into water streams that are converted into N_2O offsite [161]. A prerequisite for NO_X emissions is the availability of N, which is determined primarily by the mineralisation of soil organic matter and N deposition. Mineralisation rates depend on the history of land use (*i.e.* previous crop, residue management and fertilisation). The major parameters controlling N_2O emissions from agricultural systems include the nature of the crop, factors that regulate N availability (fertiliser management: type, quality and timing of application), soil conditions (fertility, carbon and moisture contents, pH) and climate (temperature). Inputs from crop residues in agricultural fields are important sources of C and N for nitrification and denitrification.

It has been observed that: (i) there is a strong increase of N_2O emissions with N application rates; (ii) warm climates show higher N_2O emissions than temperate climates; and (iii) fertile soils with high organic C and N contents show higher emissions than less fertile soils [160]. Emissions from grasslands are lower than for crops. Leguminous crops show N_2O emissions that are of the same level as those of fertilised non-leguminous crops. This implies a role of BNF in N_2O emissions. Fine soil texture, poor drainage and neutral to slightly acidic soils favour N_2O emission. As N_2O emissions vary with experimental conditions such as air temperature, precipitation, pH and edaphic characteristics, they vary both temporally and spatially and are therefore difficult to quantify.

For global estimates of N_2O and NO emissions and NH_3 volatilisation losses from fertiliser and manure application to fields

used for crop production, *cf.* Ref. [160]. Reported estimates of agricultural gaseous emissions vary considerably. N_2O and NO emissions by fertilisers are estimated at approximately 0.8% and 0.5% of nitrogen fertiliser input, respectively. NH_3 loss from mineral fertiliser use and animal manure is 14% and 22%, respectively. Fertiliser induced N_2O emissions differ greatly between fertiliser types (ranging on average from 0.1% to 1.9%) [160]. The highest fertiliser induced emission rates are for urea and other straight N fertilisers (primarily ammonium bicarbonate used in China) and the lowest for organic fertilisers. According to Ogle et al. [162] 2–2.5% of N added to soils is emitted as N_2O either directly on-site or indirectly with N loss through leaching, runoff and volatilisation, which is lower than a previous estimate of 3–5% emission [163]. Direct and indirect soil N_2O emissions associated with soybean production in US agricultural regions vary from about 1.0 to 2.0 t CO_2 eq/ha/yr in total [162]. Indirect emissions account for about 17% of the total soil N_2O emissions from soybean production.

The rates of converting nitrogen in soil and water streams to N_2O emissions to the air are highly uncertain [161,163]. GREET 1.8 takes into account the nitrogen in N fertilisers and in residual biomass in estimating N_2O emissions from crop farming and applies a conversion rate of direct and indirect N_2O emissions of 1.325%. In 1996, IPCC considered nitrogen input to soil from BNF by legume crops in estimating N_2O emissions from soil. The emission factor for BNF was estimated at 1.25% of fixed N. However, in 2006, IPCC elected not to consider this nitrogen input anymore because of lack of evidence of significant emissions from the nitrogen fixed by legumes. Consequently, the widely used current practice of applying the IPCC (2006) guidelines for modelling soil GHG emissions in LCAs of agricultural products does not include BNF as a direct source of N_2O but relies solely on the nitrogen inputs from crop residues (above and below ground) to account for all legume N_2O emissions [161]. This model might well turn out to be inappropriate in case of N_2O emissions from legumes as it ignores the seasonal N_2O emissions in the late-growth stages of soybean. It has been pointed out that there is almost an order of magnitude difference between the worst-case (high) N_2O emissions from crop residue and the conservative (low) N_2O emissions in the late-growth stages (crop residue emissions are smaller by a factor of 5 to 10) [164]. While previous IPCC (1996) methodology overestimated N_2O emissions from biological nitrogen fixation (3.2 to 5.0 kg N_2O-N/ha [165]) the current standard more likely underestimates the BNF contribution to GHG emissions for soybean cultivation.

The typical mean value of 1.2 kg N_2O-N/ha/yr emission reported for N fertiliser application rates of 1–50 kg/ha [160] differs considerably from N_2O field emission values of 350 kg N_2O/t soybeans calculated by Ref. [46] in accordance with IPCC 2006 guidelines, and the EU RED default value of 800 kg N_2O-N/t.

NO_X flux data from leguminous plants are highly debated. N_2O emissions of soybean are generally low, but with high peak emissions in the last stages of the crop life cycle (harvesting period) [166,167]. Estimates indicate 1.5 kg N_2O-N/ha [167], which means a significant source of GHG emissions in soybean production. Matters get more complicated when synthetic nitrogen fertilisation and bacterial inoculation are added. While soybeans show significant (seasonal) N_2O emissions from BNF – ignored in LCAs – there is considerable uncertainty in quantification and consequently on GHG emission savings. Little information is also available about the N_2O emissions emanating from fallow areas. In extreme cases N_2O emissions from set-aside land can be as high as those from areas under agricultural use [168]. Nitrous oxide is also key to ozone depletion.

Direct soil N_2O emissions can be reduced through: (i) adoption of improved N management practices (avoiding over-application of fertilisers using soil tests); (ii) use of precision farming practices (application of N at the time of crop demand); and (iii) use of nitrification inhibitors. A significant GHG reduction is possible by moving timing closer to crop needs and application deeper into the soil. Timing of nitrogen application makes a difference just as big as N fertiliser type.

Important differences have been reported in the contributions of soybean cultivation to the global warming potential (GWP). In the absence of land-use effects in the United States, N_2O emissions of the agricultural phase (typically 10–20 g CO_2 eq/MJ) contribute 50–75% to GWP. On the other hand, in Argentina land-use change emissions account for 77% of total GWP of the feedstock production process and as a result N_2O only for 16% of GWP of the agricultural phase [38]. In Brazil, N_2O emissions are responsible for 22% of total GWP of the cultivation stage.

The nitrogen cycle in agricultural systems is complicated and nitrate leaching from soils is a complex problem [169]. Only 25% of US soybeans receive N fertilisers, yet agricultural fields discharge appreciable nitrate runoff during the soybean growing seasons. Nitrate emissions from fields are highly variable depending largely on weather patterns, agricultural practices and soil properties. Miller et al. [170] have estimated nitrate emissions from soybean fields as 5–60 kg NO_3^--N/ha (median 16.4 kg NO_3^--N/ha). Strategies for reducing nitrate loss through drainage include improved timing of N application at appropriate rates, diversifying crop rotations, and reduced tillage. Soybean production can limit fertiliser-derived nitrogen runoff due to its nitrogen fixing capacity.

The substantial increase in the flux of reactive nitrogen contributes to several environmental problems, including global climate change, eutrophication and hypoxia, and acid deposition. Food production accounts for 75% of anthropogenic nitrogen due to the manufacture of synthetic fertilisers and BNF from cultivated crops such as legumes and rice, while combustion of fossil fuels contributes only 15% of the anthropogenic reactive nitrogen in the environment. In addition to N_2O and NO_X emissions from the combustion of fossil fuels associated with energy use from on farm processes and fertiliser production, agriculture is also responsible for NH_3, N_2O and NO_X emissions evolving from fields, and NO_3^- in surface water runoff.

Manure is applied to only 6% of soybean crops in the US Corn Belt [170]. Manure fertilisers show relatively high volatilisation rates during application. In corn–soybean rotations corn is responsible for the bulk of nitrate emissions on an absolute basis, but soybeans – with their low product yield per hectare – for the majority of emissions on a mass basis. Soybeans also possess a much higher nitrogen content. N_2O and NO_X emissions for soybeans and corn are comparable. Ammonia volatilisation depends on fertiliser application, which occurs on only 25% of soybean crops.

Apart from global warming, another dominating impact category for soybean cultivation is acidification. Fertilisers disturb the acid-base equilibrium in the soil leading to acidification. Production of SME increases acidification compared to petrodiesel, but fossil energy consumption also causes acidification. Acidification is even increased if biomass is used to replace fossil resources used for the production of energy (power/heat) and transportation fuels. The specific acidification potential is largely caused by SO_X and NO_X emissions resulting from incineration processes. The acidification potential (AP) is very sensitive to transport of soybeans by truck and therefore to the transport distance. Eutrophication is not a major problem in soybean cultivation if excessive use of fertilisers in avoided [41]. The agricultural sector should be careful in its fertiliser choice and use.

Although the environmental focus is mainly on savings of non-renewable energy resources and GHG emissions on a *global* scale, production of biomass is often associated with adverse environmental effects as eutrophication of surface and ground water on a *regional* level. Ecotoxicity problems in soybean cultivation mainly

stem from nitrate, phosphate and cypermethrin emissions. In Argentina soy is the main crop responsible for the strong growth of agrochemical use (herbicide glyphosate, 70%; insecticides, 17.2%; fungicides, 6.4%; seed treatment fungicides, 4%; fumigants, 2%) [171]. Use of pesticides in soybean cultivation is quite high. Pesticides are used at every production stage from pre-seed germination to post-harvest. The initial average of 2.10 L of glyphosate per hectare of RR soybeans in 1996/1997 has increased to 10.9 L/ha in 2009/2010. In all, glyphosate use in Argentina has increased from 1 kt in the mid-90s to 20 kt (2000) and 45 kt (2004) [131]; for the 2009/2010 season even a consumption of 200 ML has been reported [172]. This pesticide causes health problems and negative environmental effects on biodiversity and aquatic life [144,171,173]. The European Food Safety Authority (EFSA) is in the process of assessing glyphosate. Increased reliance on a single herbicide is a disadvantage of no-till systems and accelerates the emergence of genetically resistant weed phenotypes [174]. The pyrethroid-based pesticide cypermethrin, used for soybean production in Argentina for caterpillar control, as well as for rape and palm oil production elsewhere, is mainly responsible for the terrestrial and aquatic toxicity, even though applied in low concentrations [38]. Other, lower toxicity pesticides are used in USA and Brazil, with no effect on TETP and AETP. Human toxicity potential (HTP) is also partly on account of cypermethrin application in the agricultural phase (16%) and of benzene emissions during land provision (57%). The net environmental effects of RR soybeans in Argentina were judged positive by some [175] but negative by others [144,171].

As the crop cultivation stage makes a significant contribution to the overall environmental impacts it is important that production system and scale minimise the total environmental load. Although GHG emissions from the production and use of fertilisers have increased with agricultural intensification, these emissions are small compared to those that would have been generated by conversion of additional forest and grassland to farmland. Agricultural GHG emissions cannot be expected to be eliminated but might be reduced, *e.g.* via increased sequestration of carbon in agricultural soils [176]. Soybean sequesters less CO_2 (3.52 t/ha) and releases also less O_2 (2.56 t/ha) than oil palm (29.3 and 21.3 t/ha, respectively).

There are opportunities to reduce agricultural GHG emissions and increase soil carbon sequestration. GHG emission reductions always entail costs but high cost does not always result in large GHG reductions. The Global Research Alliance on Agricultural Greenhouse Gases, launched in 2009, aims to reduce GHG emissions and to sequester carbon in soil, and focuses on technologies and practices that will help deliver ways to grow agricultural products without incrementing GHG emissions [177,178]. Early 2010 Argentina joined the Global Research Alliance on Agricultural Greenhouse Gases. The efficiency and productivity of agricultural systems may be improved through ecologically based management practices and techniques to meet the increasing demand in a sustainable manner. Improved soil cultivation practices, *e.g.* extensive and low- or non-tillage farming, can reduce fertiliser losses substantially by: (i) reducing the total amount of fertilisers applied; (ii) improving the seasonal management of fertiliser application; (iii) reducing overall soil erosion from agricultural land; and (iv) precision farming [72].

5.2. Industrial phase

Biodiesel plants can be co-located at the oilseed crusher/extraction/refining plant or they can be stand-alone facilities at different locations. There are numerous examples of both business models in the biodiesel industry. In Argentina crusher annex biodiesel facilities are most common. Industrial biodiesel processes are well established. Biodiesel is conventionally produced by transesterification of vegetable oils or animal fats using an alcohol (usually methanol) and a catalyst (alkaline or acid) yielding a mixture of fatty acid alkyl esters and the co-product glycerol. The process generally uses pre-extracted oil as the raw material. Production of 1 L of biodiesel requires 0.88 kg of virgin vegetable oils. Biodiesel energy use typically amounts to 0.032 kW h of electricity and 20.2 L NG per litre biodiesel. In addition to methanol various other chemical inputs are required (*e.g.* $NaOCH_3$, NaOH, HCl, H_3PO_4, citric acid). The biodiesel production process produces 0.106 kg/L glycerine and 0.002 kg/L fatty acids. The major steps of the production process involve reaction (catalytic transesterification), methanol recovery, separation of biodiesel from glycerol, biodiesel purification, and glycerol purification. In most soy biodiesel LCAs the conventional alkali-catalysed transesterification process has been assumed.

More efficient biodiesel process designs must be developed in order to enhance the profitability of biodiesel production (at present highly compromised, in particular as a result of structural overcapacity). Use of oscillatory flow reactors is believed to lead to lower operating costs and investments [179]. According to Myint [180] the recommended process design consists in separation of biodiesel and glycerol first, with removal of methanol next, followed by water washing. Both alkali- and acid-catalysed *in-situ* transesterification of dried soybean flakes have been described [181,182]. This direct process, which eliminates the air-polluting solvent extraction process step from the soy biodiesel life cycle, is energetically attractive but not yet cost effective - and therefore has not been implemented on a commercial scale - and requires further development [183]. Flaked-soybean biodiesel is more expensive than refined oil soydiesel [184].

Biodiesel plant scale is an important process variable but scale effects have not explicitly been compared in soy biodiesel LCAs, at variance to rape biodiesel pathways [45,185]. Where cultivation is not the dominant step regarding environmental and energy requirements (US and Argentine conditions [39,50]), the effect of different industrial production scales on the whole life cycle of soy biodiesel should be significant. Clearly, production costs are lowest for large-scale production.

Some of the benefits connected with the use of soy biodiesel as compared to conventional diesel include enhanced biodegradation, reduced toxicity, lower GHG emissions, increased flash point and lubricity. The usefulness of soy biodiesel as an alternative fuel is limited in its commercial application by the oxidative instability and cold flow (only in northern climates), in addition to cost. Modifying the fatty acid profile of commodity soybean oil may increase the attractiveness of soy biodiesel [186].

The fossil energy and GHG savings of conventionally produced biodiesels are critically dependent on manufacturing processes (WTW) and the fate of by-products. In LCAs the lowest energy and emissions savings are reported when all inputs and emissions are attributed to biodiesel (no allocation).

The biodiesel transport to port phase is significant in the US pathway (1500 km), negligible for Argentina (integrated vegetable oil mills – transesterification units near ports). Transoceanic transport represents 57%, 43% and 27% of CED and 55%, 43% and 27% of GWP of the transport phase for Argentina, Brazil and United States, respectively, reflecting the decreased distances to Europe [38]. It should be noticed, however, that at present virtually all Brazilian biodiesel is for domestic use.

5.2.1. Energy accumulated in biodiesel life cycle

Energy accumulated in biodiesel fuel and its by-products is a relatively fixed value; consequently, the largest influence on the energy balance is made by the energy demands for biodiesel fuel

production. Biodiesel (EROI≈3.2) is less energy-intensive than bioethanol (EROI≈1.3) as the manufacturing process involves only relatively low-temperature, low-pressure steps. The total energy consumption in the SME life cycle is mainly on account of cultivation, oil extraction and transesterification. Energy consumption connected to industrial operations (oil extraction plus transesterification) and transport is directly related to the quantity of seed to be processed, *i.e.* related to grain yields. Per unit seed yield, farm production energy inputs for soybean are much lower than for canola, *cf.* Fig. 3 [42]. Energy required by processing and oil extraction, per unit oil, is higher for soybean. Energy required for transesterification per unit extracted oil is the same for both sources but less soy oil needs transesterification. Estimates of energy required to process oilcrops vary widely, depending on extraction process, plant size and age, transesterification technology and performance, energy mix, system boundaries, and method of reporting energy use. New soybean crush plants use about 42–58% less energy than older plants [50,187]. Differences in processing the oilseeds include the drying and extraction modes.

Many biodiesel plants do not have crushing capacity, they purchase oil and have it transported to their plant. The energy required to transport oil to a biodiesel plant is about 0.17 MJ/L (biodiesel share) per 920 km (571 mi) [50]. When adding this energy to the inventory, the fossil energy ratio (FER) decreases.

Oil is most commonly extracted from soybeans using hexane extraction. Oil refining may eventually be required before transesterification. Energy required for transesterification of extracted oils should be the same for sources with similar free fatty acid (FFA) contents [42].

In terms of non-renewable energy consumption (CED) most soy biodiesel pathways are below the fossil reference, with an Argentinean pathway involving land-use change with soybean cultivation in deforested areas being among the most energy-consuming [38]. For soy biodiesel an interval of primary energy saved *vs.* the conventional diesel reference has been reported of 16.5–22 GJ/ha (*cf.* 40–60 GJ/ha for sunflower biodiesel) [188]. Palm oil biodiesel has a much higher energy performance [189]. The impact of biodiesel production on CED is usually highly dominated by the agricultural phase (Argentina 61%, Brazil 66%, EU 62%, CH 57% and Malaysia 47%) [38], except for the case of US soy biodiesel where the industrial phase dominates (56%) [50]. A typical breakdown for modern agricultural and industrial process steps of the fossil energy use for biodiesel from US soybeans is as follows: cultivation, 17%; drying/extraction/refining, 19%; transesterification, 56%; transportation/distribution/storage, 8% [50]. This differs considerably from the values for rape biodiesel (38%, 18%, 40% and 4%, respectively), where the cultivation stage is more energy intensive [16]. However, great differences are noticed, *cf.* Tables 2, 3, 13 and 20. In particular, the total primary energy input varies widely from 5.9 MJ/L biodiesel in US conditions [50] to 1.02 MJ/MJ (or 33.3 MJ/L) for Chinese conditions [21]. The overall lower CED value for USA as compared to Argentina is on account of lack of deforestation, 2% higher crop yield, lower use of agrochemicals and shorter transport distances (*cf.* Table 20). The US logistic system is more efficient. In an Australian soy biodiesel LCA with economic allocation, based on local agricultural practice and Sheehan's processing data an energy requirement of 0.45 MJ/MJ was reported [53].

Methanol used for transesterification contributes considerably to the primary energy and CO_2 output of biodiesel. CED can be reduced by using sugarcane-based ethanol. Soybean ethyl ester production started in Brazil in November 2000 [190]. In 2002, ethanolysis of vegetable oil was the main proposed route in the Brazilian fossil diesel substitution program PROBIODIESEL. Heterogeneous catalytic transesterification (a high energy-demanding process which yields high-purity glycerol) leads to a decrease in energy performance of the transesterification step of 72% (for rapeseed oil) and a decrease in EROI [86]. All process steps require careful optimisation.

Apart from important differences between the processing steps the total energy requirements for small- and large-scale (rape) biodiesel production (per unit) are similar [185]. The energy requirement in the transesterification stage depends strongly on the methanol recovery.

Gazzoni et al. [112] have reported a fossil energy ratio (FER) of 3.5 for soy biodiesel produced in Brazilian conditions (2005). The use of fertilisers and pesticides for soybean cultivation is high in both Brazil and Argentina. Soybean yields in Argentina, Brazil and USA are quite similar. While higher FER is desiderable to ensure that biofuel is renewable, it does not guarantee that biodiesel will also be economically viable.

In the EUCAR/CONCAWE/JRC study, which concentrates on fuel production and vehicle use as the major contributors to lifetime energy use and GHG emissions, a WTW fossil energy saving requirement of 100 MJ/100 km (in a 2010+ vehicle) has been given for SME (with glycerine as chemical, meal as animal feed in Brazil, mill in EU) with 49% fossil energy savings compared to conventional diesel fuel [191]. The fossil energy saving is smaller than for palm, sunflower or rape biodiesel pathways. The observed fossil energy savings do not imply that the soy biodiesel pathway is inherently energy efficient. In fact, the total energy involved in the pathway is several times higher than the fossil energy involved in the pathway itself and also higher than the energy involved in producing conventional fuels. Biodiesel is a fundamentally inefficient way of using the resource biomass.

Energy balances (EROI) of SME are unfavourable when compared to perennial crops (*e.g.* average energy ratio of 9.0 for palm oil) as the net energy production per hectare is low. In the past, in some cases the balance was reported being negative. Some other reports have indicated an energy ratio of less than one because the actual energy in the oil was included, as well as the energy to produce the oilseed, while other studies have included the human energy input associated with the production of the oilseed and biodiesel [29,84]. Others did not include the oilseed energy nor human energy [42].

Hectare yields can fluctuate considerably both regionally and seasonally. The area-related biodiesel yield is the highest energy amount of biodiesel that can be generated from the initial products obtained from one hectare of area under cultivation. The area-related final energy yield is the highest amount of bioenergy that can be generated from the products plus by-products obtainable on one hectare of area. The total energy yield is thus composed of the area-related biodiesel yield, the energetically utilisable by-products and eventually the heat and electricity provided during biodiesel generation. As by-products can be used in different ways, allocation of an energy yield is fraught with difficulties. Moreover, by-products can be credited in different ways (based on mass, economic or energetic value).

5.2.2. Life-cycle GHG emissions

A fundamental principle regarding the sustainability of biofuels is its potential of saving GHG emissions as compared to the substitute fossil fuels. Life-cycle analyses demonstrate that most current (1st generation) biodiesel technologies deliver 40–60% life-cycle GHG savings from road transport compared to that of conventional diesel if (direct or indirect) land-use change causing significant losses in carbon stocks is avoided (*cf.* also Table 22). According to the Gallagher review estimated GHG emissions savings of soy biodiesel compared to conventional diesel range from 6 to 67% [17] (or typically 40% [11]), excluding emissions due to land-use changes. In the most favourable case SME (soybean methyl ester) can save 56% of the GHG emissions required for

conventional diesel [154] and 82% of the fossil energy [50]. GHG emissions of soy biodiesel derived from corn–soy rotations are 59% those of diesel fuel [20]. For soy biodiesel an interval of GHG saved *vs.* the conventional diesel reference has been reported of 0.40–1.05 t CO_2 eq/ha (*cf.* 1.7–4.0 t CO_2 eq/ha for sunflower biodiesel) [188]. The typical and default GHG emissions for soy biodiesel have been quoted as 50 and 58 g CO_2 eq/MJ respectively, as compared to 10 and 14 g CO_2 eq/MJ for used cooking oil (UCO) biodiesel [11]. Life-cycle emissions of 0.034 kg CO_2 eq/MJ were reported for an Australian soy biodiesel [53].

The EUCAR/CONCAWE/JRC study [191], which is not a life-cycle analysis, has modelled as the principal pathway soybean farming in Brazil and crushing in Europe with the meal replacing soymeal which would otherwise be imported from Brazil. In this way, shipping to EU of the soymeal fraction of the soybeans is cancelled by the credit from avoided soymeal import. For SME (with glycerine as chemical, meal as animal feed in Brazil, mill in EU) a WTW GHG requirement of 90 g CO_2 eq/km (in a 2010+ vehicle) has been quoted with a 40% GHG emissions savings compared to conventional diesel fuel [191]. Both the GHG emissions savings and fossil energy savings are smaller than for palm, sunflower or rape biodiesel.

The reported wide spread in GHG values ranks soy biodiesel both as the best and worst biodiesel. The best results conform to the minimum EU sustainability criterion (35%), whereas the worst results (6%) already denote non-conformity even in the absence of land-use effects. The large variety of results denotes a considerable heterogeneity of production conditions, as reported in pathways of Section 4, which leaves significant room from improvement. Using 1990 data Sheehan et al. reported lower GHG emissions for soy biodiesel use as compared to mineral diesel, namely 78% reduction of CO_2 emissions and 3% of methane [29]. Using improved 2006 US data Huo et al. [47] have reported a significant reduction of WTW GHG emissions of soydiesel *versus* petrodiesel, namely 94% using the displacement approach and 68% for allocation methods. US soy biodiesel shows the best performance in terms of GWP and CED. When the most recent standard values are employed biodiesel produced from US soybeans is capable of reducing GHGs by 56% compared to the fossil reference [52,154], which exceeds the target of 35% GHG mitigation required in EU RED. The GHG balance of biodiesels (not considering land-use change) is strongly influenced by the energy ratio between the product output and input values (as fossil energy).

When upgrading a vegetable oil to a road fuel, the transesterification and hydrotreating routes are broadly equivalent in terms of GHG emissions (*cf.* Fig. 2). Whereas biodiesel is less energy-intensive than ethanol, in GHG terms the picture is different because of the nitrous oxide emissions which account for an important fraction of the total and for most of the large variability ranges.

Life-cycle GHG emissions for biodiesel show considerably higher uncertainties than energy efficiency values. These uncertainties are on account of the allocation for the large amount of meal co-product credits, soil carbon emissions from direct LUC and N_2O release from cultivated soil. Obviously, median-value life-cycle GHG emissions decrease by allocation as emissions are partitioned between co-products based on specific relationships. The substitution method, which is favoured in LCA according to the ISO 14044 standard, subtracts the credits associated with displaced products from the biodiesel chain. When land-use change is excluded from the analysis, the uncertainty in total GHG emissions still derives mainly from the cultivation stage with its great variability in terms of fuel and fertiliser inputs, and highly uncertain parameters such as field N_2O emissions. It is noticed that in most LCAs – even the most recent USB studies [46,52] – the effects of BNF were not explicitly accounted for (*cf.* also Table 20), which leads to an underestimate of GHG emissions. The uncertainty in industrial conversion processes is small, both in terms of GHG and energy. Regional transportation hardly contributes to the overall GHG balance.

Whereas most studies have concluded that substituting fossil diesel by biodiesel leads to lower overall GHG emissions, a few studies have drawn the opposite conclusion on the basis of certain assumptions or in certain conditions. Estimates for fossil fuel-related CO_2 emissions vary considerably [82,84]. Zah et al. [82] have given data for cumulative energy demand (CED) for conventional diesel (100%) and biodiesel based on American soybean (~70%) and European rapeseed (~60%), using economic allocation. If it is assumed that CED of biodiesel is only 30% of that of conventional diesel, then the values for biogenic emissions for soybeans should not exceed 2.1 kg CO_2 eq/kg BD, quite opposite the findings (2.7–32.5 kg CO_2 eq/kg BD) [4]. Accordingly, biogenic emissions of carbonaceous GHGs and N_2O in the life cycle of Brazilian soybeans, grown for up to 25 years with no tillage on arable soil for which tropical rainforest or Cerrado (savannah) has been cleared, are worse than for conventional diesel.

In principle, soy biodiesel can be produced in an environmentally friendly way, depending on the soybean cultivation practices without direct or indirect land-use change effects and production technology. Table 17 shows a breakdown by process steps of GHG emissions from soy biodiesel. Fossil fuels are used in the agricultural phase (fertilisers, pesticides, machinery), in transesterification, and for transporting the raw materials from the field to the processing plant and from there to the final users. Plant scale is not important for GWP as long as the impact of agriculture outweighs all other factors [45,185]. This is the case for rape biodiesel but not for all soydiesel pathways [50]. At equal environmental load, larger plants are to be preferred in terms of production costs. In the reported Argentinean pathway with deforestation the environmental impact of the agricultural stage (3.5 kg CO_2 eq/kg or 85%) is much higher than that of the fuel processing stage. Biodiesel generates lower emissions during extraction (4%) and transesterification (8%) [38]. Transportation (4%) for the Argentinean pathway only plays a minor role, even when biodiesel is produced overseas and transported with tank ships. The inland transport from transesterification plant to port phase is most significant for Brazil, less so for USA (9%, where biodiesel is transported over 1400 km by train and 100 km by truck to port) and low in Argentina (about 100 km). Transoceanic transport represents 43%, 27%, and 55% of the GWP of the transport phases for soy biodiesel from Brazil, USA and Argentina, respectively. For the US, the main contribution is the rail transport of biodiesel from the production site to the exportation port (31% and 34% of GWP and CED of the transport/distribution phase, respectively), followed by transoceanic transport (22% and 21% of GWP and CED of the transport/distribution phase, respectively). The actual vehicle operation is CO_2-neutral as the amount of CO_2 emitted by biodiesel in the combustion stage is the same as that absorbed by the plant during its growth through photosynthesis. Biodiesel use is characterised by a small increase in NO_X compared to petrodiesel [192].

Calculation methodologies for GHG emissions according to the EU Renewable Energy Directive [11] and EPA [36] are different (Table 21). EU RED has standardised the methodology for calculation of GHG emissions (g CO_2 eq/MJ) from production and use of biofuels. Emissions from the manufacture of machinery and equivalent are not taken into account. In certain conditions a bonus of 29 g CO_2 eq/MJ biofuel is attributed if biomass is obtained from restored degraded land. Table 22 lists typical and default values for biofuels if produced with no net carbon emissions from land-use. The default value for soy biodiesel (31%), produced without land-use change, is below the required minimum (35%).

Table 21
Main differences between EU RED and US EPA GHG calculation methodologies for biodiesel.

Parameter	EU RED	US EPA
Base year	2008	2005
Reference value for diesel ($g\ CO_2\ eq/MJ$)	83.8	91.4
Allocation method	Net calorific value	System expansion/economic value[a]
Indirect land-use change	Excluded	Included
GHG saving threshold (%)	35–60[b]	50–60[c]

[a] System-dependent allocation procedure.
[b] Current limit 35%, to increase to 50% in 2017, and 60% thereafter.
[c] The 50% for biodiesel from waste oil and 60% for cellulosic biodiesel.

Table 22
Life-cycle greenhouse gas emissions savings from biofuels (produced with no net carbon emissions from land-use change).

Biofuel	GHG emissions savings (%)	
	Typical value	EU default value
Rapeseed oil	58	57
Rapeseed biodiesel	45	38
Hydrotreated rape oil	51	47
Sunflower biodiesel	58	51
Soybean biodiesel	40	31
Palm oil biodiesel	36/62[a]	19/56[a]
Waste oil biodiesel	88	83
Sugarcane ethanol	71	71
Corn (maize) ethanol	56	49
Wheat straw ethanol[b]	87	85
Waste wood FT diesel[b]	95	95

After Ref. [11].
[a] Process with methane capture at oil mill.
[b] Pre-commercial *cq.* future biofuel.

Soydiesel trade to EU-27 requires submittance of actual emission savings.

In (sub)tropical agriculture it is primarily the clear-cutting and burning of rainforests that release the largest quantities of CO_2, cause an increase in air pollution and lead to massive impacts on biodiversity. However, unlike the case of fossil fuel diesel, the environmental impacts of soy biodiesel can be reduced by various measures. Regional differences in the way energy plants are cultivated do have a relevant effect on the overall result. Changes in agricultural practices allow for larger improvements in the reduction of life-cycle emissions of GHGs than industrial biodiesel production technology [69,193,194]. Improving agricultural practices should also be an important focus for cleaner production of soy biodiesel. These may include increasing soil carbon stocks, *e.g.* by conservation tillage and return of harvest residues to arable soils [117], and improving N-efficiency by precision farming [194] and/or improved irrigation practices [195]. An optimal ratio of energetic yield and low environmental impact can be achieved through variety and crop rotation. These improvements lower the life-cycle and N_2O emissions. However, biodiesel is far from being a cost-efficient emission abatement strategy [19].

Conventional LCAs, which mostly focus on pathways which do not require diverting the productive capacity of land from alternative uses, find that biodiesel reduces GHG emissions compared with fossil diesel. Without land-use change, soy biodiesel is estimated to generate GHG savings of about 45 $g\ CO_2\ eq/MJ$ (*cf.* Table 23). Typical LCAs assign biofuels the gross benefit of using land, whereas they should only assign a net benefit. A net GHG benefit is most easily achieved by using waste carbon. Table 22

Table 23
Estimated biodiesel emissions and savings ($g\ CO_2\ eq/MJ$) in 2020 for additional EU mandate.[a]

Biofuel	Direct savings[b]	LUC emissions[c]	Net savings[c]
Rapeseed	50	54 (67)	−4 (−17)
Sunflower	58	52 (61)	6 (−3)
Soybean	45	56 (71)	−11 (−26)
Palm fruit[f]	58	54 (85)	4 (−27)
Biodiesel/bioethanol[d]	57	38 (50)	19 (7)
	In percentage of GHG savings[e]		
Rapeseed	55	60	−5
Sunflower	64	58	6
Soybean	50	62	−12
Palm fruit[f]	64	60	4
Biodiesel/bioethanol[d]	63	42	21

After Refs. [196,197].
[a] For trade policy status quo.
[b] Based on improved technology and yields in 2020.
[c] In parenthesis effects of added revised peat emissions [198].
[d] Biodiesel/bioethanol ratio 72/28.
[e] With a 90.3 $g\ CO_2\ eq/MJ$ reference for fossil fuel.
[f] Methane capture at mill technology.

shows that cellulosic biofuels are predicted to have better GHG balances than those based on temperate crops because of forecasts of reduced growing inputs and energy needs in refining.

Soy biodiesel has the potential to reduce GHG emissions in the transport sector if land-use change can be avoided. Current LCAs of GHG effects fail to take account of either indirect land-use change (ILUC) or avoided land use from co-products and create an over-optimistic picture by encouraging increased use of feedstocks that lead to higher net land use. For US soy-to-biodiesel with a GHG saving of 33% excluding the impacts of land-use change estimates of carbon payback times of 14–96 yr (grassland) and of 179–481 yr (forest) have been given [199]. Although the precise impact of ILUC on EU targets or feedstocks is highly uncertain, the effect reduces or even totally eliminates the GHG benefits of biofuels. Land-use change generally has dramatic effects on life-cycle GHG emissions (*cf.* Section 5.3.2). In the past, the UK Renewable Fuels Agency has released a conservative estimate for the GHG balance of imported soy biodiesel produced in Argentina (1.8 $kg\ CO_2\ eq/kg$), which is considerably lower than the value of 4.0 $kg\ CO_2\ eq/kg$ reported by Panichelli et al. for an Argentine pathway including the effects of deforestation [38] and values given in Table 35 for various DLUC scenarios [63].

Life-cycle GHG emissions of soy biodiesel (Brazil) including impacts from indirect land-use change have been estimated as 76 $kg\ CO_2\ eq/GJ$ (range of 51 to 101 $kg\ CO_2\ eq/GJ$), or a net loss of 12% relative to fossil diesel (range from 17% net gain to 41% net loss) [200]. Deforestation for soybean cultivation significantly contributes to an increase in GHG emissions and represents 70% (Brazil) to 77% (Argentina) of the GWP of the soy feedstock production process [38]. For GWP the contribution of feedstock production is generally quite high: Argentina 80%, Brazil 83%, EU 79%, Switzerland 83%, Malaysia 62%, and USA 54% [38].

5.2.3. *Environmental profiles*

Environmental sustainability of biofuels has many aspects, such as GHG balance, biodiversity, food crop displacement and prices, indirect effects, societal concerns, soil fertility, landscape values, water use and management, and other impacts.

Whereas the accumulated non-renewable energy demand (CED) correlates with GHG emissions, the situation differs for other environmental indicators. First-generation biodiesels do not offer environmental and human health benefits on all fronts.

Actually, there are few biogenic energy carriers that give positive results both as regards GHG emissions and environmental LCA. Used cooking oil (UCO) biodiesel is such an example. While US soy biodiesel offers a GHG mitigation potential of 56% as compared with the fossil reference, there is a trade-off between minimising GHG emissions and lower total environmental impacts, as for most biofuels [154]. For instance, SME causes more emissions in the impact categories acidification, terrestrial eutrophication, photo-oxidant formation and land use, compared with LPG [62], which is largely related to the growth of crops for biodiesel production. The biodiesel life cycle imposes a higher burden on water resources than the petrodiesel life cycle, namely 86.3 kg/bhp h [29].

In comparison to the environmental impact with low-sulphur diesel (LSD, 55.1 MJ eq/kg) all biodiesel pathways perform worse than the fossil reference for almost all the categories (except for CED and GWP of some pathways) [38,82]. GWP for the production stage only amounts to 0.59 and 0.60 kg CO_2 eq/kg for diesel and LSD product, respectively. In conditions of considerable variations in the previous land use the production (cultivation) stage of soybean oils results in very high GHG emissions (*cf.* Table 35). Net life-cycle CO_2 emissions from B100 are reduced by 78.5% compared to petroleum diesel [29]. For soy biodiesel 84.4% of the CO_2 emissions occur at the tailpipe. The remaining CO_2 comes about equally from soybean agriculture, crushing and conversion to biodiesel. Areas of concern for soy biodiesel are its NO_X and total hydrocarbon (THC) emissions. The use of B100 (in urban buses) reduces life-cycle emission of PM, CO and SO_X by 32%, 35% and 8%, respectively, relative to petrodiesel, but NO_X emissions increase by 13.4% [29]. The increase in hydrocarbon emissions is due to the release of hexane during soybean processing and to volatilisation of agrochemicals applied on the farm. The utilisation phase adds considerably to the GWP of the fossil reference as biogenic carbon uptake is not compensated as in case of biodiesel, significantly increasing the GWP of the fossil reference. Nevertheless, Argentinean and Brazilian biodiesels result in higher GWP [38].

The acidification potential is mainly on account of the utilisation phase (54% of AP for the Argentinean pathway) as a consequence of N_2O emissions. Only the US pathway shows a lower AP compared with the fossil reference. The eutrophication potential (EP) for biodiesels is higher than that of the fossil reference, and is mainly due to the feedstock production stage and much less dependent on utilisation of the fuel (72% and 22% for Argentina, respectively) [38]. Soybean requires less mineral fertilisers than other crops (such as corn or rapeseed), therefore have less impact on acidification and eutrophication. Halogenated organic emission in crude oil extraction and refining has great destructiveness to the ozone layer, affecting ODP. Pesticide use is largely responsible for almost all the terrestrial and acquatic ecotoxicity (TETP and AETP, respectively) as well as for human toxicity (HTP), *cf.* Section 5.1.2. Pesticide use also affects biodiversity. Break years tend to reduce pests and diseases, so doing away with it would tend to increase pesticide use.

Environmental burdens, which do not have a common denominator, can be expressed as one environmental index via normalisation using eco-indicators [82,201] or environmental impact points [82,202] (*cf.* also Fig. 2 and Table 24) to account for the total effects to the environment. Pennington et al. [74] have aggregated normalised potential environmental impact (PEI) categories in just one indicator or total PEI. Morais et al. [62] have applied such normalised total PEIs in recommending the environmentally most preferable fuel for Portugal (soy biodiesel or LPG).

Zah et al. [82] have described the environmental impact of the entire production chain of soy biodiesel made overseas and utilised in Switzerland (2004 data). Table 24 summarises the results. GHG emissions from US soy biodiesel were lower than those from Brazil; the latter even exceeded those of the petrodiesel reference (105%). The high value of the aggregated total environmental impact points (UBP 06) for Brazilian soybean is on account of biodiversity loss in tropical agriculture, air pollution caused by clear-cutting and the ecotoxicity of pesticides. The cumulated non-renewable energy demand (CED) correlates with the GHG emissions, but generally not with the environmental indicators. Results based on the Swiss ecological scarcity method (Environmental Impact Points, UBP 06) and the European Eco-indicator 99 method were similar. The environmental impact of agricultural cultivation of the feedstock is higher than from fuel processing. There is a trade-off between minimising GHG emissions and lower total environmental impacts. Transport of foreign biofuels into Switzerland was only considered to be of secondary importance. However, intercontinental transport accounts for 8.9 g CO_2 eq/MJ (or 21% of total GHG) for US-EU and for 13.0 g CO_2 eq/MJ for Brazil-EU [52].

Table 24
Environmental impact assessment of soy biodiesel produced in USA and Brazil and utilised in Switzerland.

Environmental impact	Soydiesel origin	
	USA	Brazil
GHG emissions (kg CO_2 eq/km)	0.091	0.192
GWP reduction (%)	48.4	–5.0
Environmental impact points, UBP 06 (Pt/km)	323	545
CED (%)	48.2	72.6

After Ref. [82].

Table 25
Projections of 2022 (bio)fuel demand (billion gal/yr).

Region	Fuel demand	Biofuels demand
US	180	36
EU-27	95	6.7
Brazil	16	8.0
China	20	3.0
India	34	6.8

After Ref. [203].

5.3. Consequences of renewable energy action plans

The amount of biofuels produced is a result of political decision making and not determined by free market trends. By early 2012 at least 46 countries had adopted regulatory policies supporting biofuels. Transport fuel-tax exemptions and biofuel production subsidies exist in at least 19 countries. National biofuel blending mandates currently in place worldwide call for at least a 60 Bg/yr biofuels market by 2022 (Table 25) [203]. Besides the EU, other major blending mandates that will drive global biofuels demand are those set in the US, China and Brazil – each of which has targets at levels in the 15–20% range by 2020–2022. The US Renewable Fuels Standard (RSF2) has set a target of 36 Bgy of biofuels by 2022; a minimum GHG savings applies to conventional biofuels. Many other countries have set biofuels targets at quite high levels (up to B20). Fulfilment of the prospected demand by 2020–2022 requires cellulosic feedstock or other advanced biofuels.

The EU Energy and Climate Change Package (CCP) of 2009 aims to ensure the EU meets its ambitious targets by 2020. Key objectives of these so-called '20–20–20' targets are: (i) 20% GHG emissions reductions from 1990 levels; (ii) 20% share of energy consumption produced for renewable sources; and (iii) 20% improvement in energy efficiency by 2020. The EU Renewable

Energy Directive 2009/28/EC (RED) [11], which specifies a 10% share of renewable energy (or 7% from 1st and 2nd generation biofuels) in road transport fuels by 2020 across the entire membership, to be met by domestic production and imports, has impact on the oilseeds market. In order to count against mandated use levels and qualify for financial supports, biofuels must comply with EU sustainability criteria. These criteria apply to both domestic and imported biofuels and feedstocks. EU RED prescribes that biofuels should not be produced from raw materials cultivated on land converted from high-carbon-stock or high-biodiversity areas, and should deliver a minimum level of direct GHG savings compared to fossil fuels. Starting in 2010, biofuels produced in new plants shall offer a minimum of GHG emissions savings of at least 35% compared with fossil fuels; for older installations this applies as from 1 April 2013—grandfathering clause. As from 1 January 2017 a reduction of 50% shall be required. Plants built in 2018 or later must show a further GHG reduction of 60%.

Implementation of the EU mandate is supposed to result in an increase in the relative consumption of bioethanol to biodiesel (from the energetic ratio of 17/83 in 2008 to 28/72 in 2020; the bioethanol share in EU-27 2012 amounted to 21.8%) [204]. In absolute terms the mandate involves greater development of biodiesel (+10 Mtoe from 9.7 to 19.7 Mtoe) than of bioethanol (+ 5.5 Mtoe from 2.0 to 7.5 Mtoe). By 2020, the EU market share for biodiesel would reach 69% as compared to 52% in 2008. Soy biodiesel will shrink (from 20% in 2008 to 9% in 2020) as a result of EU import restrictions on US biodiesel since 2009, lower Argentinean export capacity, and the relative price increase of soybeans driven by Asian growth [196].

The EU additional mandate will lead to an increase of 37% in the global production share of biodiesel and an increase of 22% for soy biodiesel (from 2.83% to 3.45% of world production). The share of soy in the EU biofuels production will rise from 6.52% (2008) to 7.45/9.90% (2020) depending on the trade liberalisation regime [196].

Global biodiesel production is expected to increase to about 42 bn L (37 Mt) by 2020 [205] and would then account for about 20% of total vegetable oil consumption as compared to 10% in the 2008–2010 period. In 2020 EU-27's renewable transport should contribute 13% to the overall renewable energy with biodiesel giving the largest contribution (65.9%), *cf.* Table 27. The EU is expected to stay the major producer (51%) and user (57%) of biodiesel. International trade is only expected to be significant towards the EU (Table 26) with Argentina being the main exporter. By 2020, vegetable oil use for biodiesel production will amount to 48% of EU's total domestic consumption [205]. The increased use of biofuels in the EU adds to the existing (and already increasing) demand for agricultural commodities. Increased demand for a specific crop can be met by expansion of agricultural land (transformation of a specific land type into arable land), intensification (increase in yield per hectare; very limited) and displacement (substitution of one crop with another). In all cases environmental burdens are subject to change.

Developing sustainable biofuels programs requires careful consideration of unintended environmental impacts. Expanded global biofuels programs are putting higher pressures on land supply and can increase GHG emissions from land-use change (LUCs). Growth in biodiesel production worldwide has severe consequences, notably indirect land-use changes (ILUCs). Indirect land use is responsible for substantially more carbon loss (up to twice as much) than direct land use [207]. However, the N_2O emissions associated with the predicted increases in fertiliser use (less relevant for soybean) might overtake carbon losses in terms of global warming potential. Best practices for nitrogen fertiliser use are urgently needed.

Government aspirations for biofuel production (European RED, US energy mandates, *etc.*) go beyond the levels that can be produced sustainably on existing arable land. Already the Gallagher review has indicated that targets higher than 5 vol% (4% by energy) should only be implemented beyond 2013/2014 at the EU and UK level if biofuels are shown to be demonstrably sustainable (including avoiding indirect land-use change) [17]. EU did not achieve its blending targets up to 2010 (target 5.75%, actual blending 4.26%) and is unlikely to meet its biofuels target of 10% (by energy) for 2020 in a sustainable manner without corrective measures. Bottlenecks are the availability of appropriate land and ensuring that only sustainable feedstock is used. EU approved sustainability standards are a step forward but only if adhered at a global level.

Early EC studies concerning the 10% of transport fuel requirement by 2020 have initially ignored land-use change outside the EU assuming heavy reliance on EU set-aside lands and sourcing 30% of cellulosic ethanol by 2020 [208,209]. However, European set-aside lands are decreasing. Meeting the EU targets alone would require already a land area from 20 to 30 Mha, for 50% located outside the EU [210].

The future biofuels demand requires more energy crops. The extent to which the additional demand for biofuels (as well as for food and feed) will be met by an increase in supply (*e.g.* land reallocation) depends on the feedstock crop. Almost 60% of the biofuel demand is met by new production. The remaining oil is displaced from other sources of demand. In some cases, this additional demand may not be matched by an additional supply. For soybean and rapeseed oil the additional demand is only partially matched by additional supply; for soybean the replacement ratio between additional supply and demand is only 40%, for rapeseed 78%. Displaced soybean oil is replaced by all the other types of vegetable oils. Additional production of palm oil and, to a lesser extent, sunflower oil is larger than the demand in their respective biodiesel sectors. Their increased production also replaces soybean and rapeseed oils used for biodiesel production and not provided for by additional productions of these oilcrops. Overall only 10% of total vegetable oils is not replaced. A reallocation of production will result. Due to the strong biodiesel component in the mandate an increase in price for oilseed crops is

Table 26
Biodiesel market outlook 2020.[a]
Source: OECD-FAO.

Market	Production (%)	Use (%)
EU-27	51	57
USA	8	9
Brazil	7	8
Argentina	9	2
India	8	8
ROW	17	16

[a] Total market volume 37 Mt.

Table 27
Biodiesel in EU-27 transport.[a]

	Year			
	2005	2010	2015	2020
Total energy consumption[b] (Mtoe)	299	313	315	312
RED transport target (%)	1.4	4.9	6.8	10.1
Total renewable transport target (Mtoe)	4.2	15.3	21.7	32.9
Biodiesel consumption	2.4	11.0	14.5	21.6

After Ref. [206].

[a] Based on National Renewable Energy Action Plans (NREAPs), *cf.* Ref. [206].
[b] For transport sector only, corrected for energy efficiency measures.

forecasted. In terms of environmental control, the greatest concern with the rapid expansion of vegetable oils is with soybean and palm oil [196].

Large-scale production of biodiesel will affect not only the liquid fuel sector, but also other sectors of the economy, including agriculture, livestock feeding, and the glycerine market. Increased production and processing of oilseeds for biodiesel will generate large quantities of animal protein meal, affecting protein meal prices and livestock feeds. Through international trade agreements regarding oilseed meals, the livestock sector plays a critical role in the biofuels dynamics. Changes in relative crop prices have economy-wide impacts and will alter cropping practices. World-wide large-scale biodiesel will likely result in oils and fats with lower food quality being used for biodiesel production.

There is general consensus that large amounts of land will be needed to produce biofuels by 2050 if aggressive biofuels plans are adopted globally, that tropical regions are important locations for growing biofuel feedstocks, and that pasture lands (broadly defined) will be a major source of lands used for biofuels [211]. In developed countries the possible area expansion is limited and the production increase is only caused by yield increase. However, growth rates of average yields have generally slowed during the last two decades, which is not surprising if one takes into account lower yields on less desirable lands. Regions where large areas of land are potentially available for biomass production are in particular North and South America, Central Africa and Oceania.

The EU *Strategy for Biofuels* [212] indicates that Europe promotes production of raw material for biofuels in extra-European countries, even though this determines another high degree of energy dependency. Europe shifts the environmental burden of energy farming (pollution, soil erosion, reduction of biodiversity, decrease in water resources and quality, deforestation) to beyond its borders, in particular to natural habitats of global importance such as the Brazilian Cerrado and IndoMalay rainforests [213]. As to the impact on ecosystems, large-scale feedstock production could well lead to habitat and biodiversity losses [214]. Vegetable oil is a commodity that is associated with these problems. Large-scale production of biofuels (accounting for over 15% of total commercial energy requirement, and probably at even much less) is constrained both socio-economically and biophysically.

In the past, the European trade pattern has been to import raw materials (oilseeds) rather than finished biodiesel. This has changed in 2007 with massive soy biodiesel imports as a result of US subsidies and Argentine tax cuts. EU RED has restricted soy feedstock and biodiesel exports because of default GHG emission savings and other sustainability requirements. US biodiesel exports have suffered by the EU's countervailing duties. Although subsidised North American biodiesel imports have been curtailed, those from Argentina and Indonesia have continued to grow (2.6 Mt in 2011). EU biodiesel import 2010 was mainly from Argentina (61.8%), Indonesia (25.2%), Canada (4.3%) and Malaysia (4.3%). Export of Argentine soy biodiesel is expected to decrease as a result of rising domestic demand; export to Spain has stopped completely after a trade dispute. European governments no longer view the rapid increase in biofuel consumption as a priority. EU's attention has shifted to setting up sustainability systems to verify that the biofuel used complies with the RED sustainability criteria.

The import of oilseeds or vegetable oils for biodiesel production (or for replacing domestic oilseeds which are diverted to oilseed manufacture) raises major questions about sustainability. One source with a potential for expansion is Brazil but the existing high demand for soybeans is locally accelerating land-use change. Sustainability certification may be considered as part of the solution.

As a benchmark for current GHG reductions of biofuel production, the European Commission has used life-cycle modelling from a CONCAWE Well-to-Wheels study [191]. For soy-based biodiesel this modelling was based on soybeans grown in Brazil (from land already in arable use), overseas transport to Europe, and conversion into soydiesel in European processing plants. The EC established both 'typical' and 'default' values for GHG savings. The only difference between these values is a 40% increase in the processing step for the default values. Default values for life-cycle emissions from biofuels produced with no net carbon emissions from land-use change are given in Table 22. The default GHG emissions saving for biodiesel from soybean oil (from Brazilian origin) was set at 31%, *i.e.* below the minimum requirement of 35%. In other words, soybeans (from whatever origin) are not considered being RED compliant on the basis of the current default value. (The EU's Joint Research Centre (JRC) is working on updating the default values of RED Annex V). Therefore the soybean feedstock supplier to the EU market needs to provide evidence of sustainability on the basis of actual values. Such values of GHG emissions can be calculated in accordance with RED Annex V. Energy allocation percentages used by EC are crude soybean oil/soymeal, 36/64 (for soybean crushing); and biodiesel/glycerine, 94/6 (for biodiesel production). Appropriate actions have been undertaken by USA [46,52,154] and Argentina [39,40,81]. Currently, still only a few EU-27 member states require sustainability certificates for biofuels and their feedstocks [215]. Germany complies with the RED sustainability criteria since 1 January 2011; other EU member states are following quickly. Since 15 December 2011 UK's RTFO has been amended to implement RED's sustainability criteria. From now on eligibility for sustainable fuel certificates – Renewable Transport Fuel Certificates (RTFCs) – depends on meeting these criteria. The UK has increased its sustainable biofuel incorporation volume from 3.5% in April 2011 to 5% in April 2013. The actual incorporation volume of 3.1% in 2010/2011 falls short of the intended obligation. With improved technology and without land-use effects all biofuels consumed in the EU in 2020 will meet the legal requirements of the RED threshold value of 50% direct savings compared to the fossil fuel standard (*cf.* Table 23). Biofuels developed from non-food sources receive preferred treatment under the agreement.

The default values of EU RED present a conservative average of applied production procedures in order to avoid use of environmentally unfavourable biofuels. The United Soybean Board (USB) has criticised that the used background data of the EU RED default value for provision of soy biodiesel are outdated, resulting in an overestimate of GHG emissions, and requires revision or even rejection of the default value for the minimum GHG reduction potential of soy biodiesel [52]. Sustainable agricultural management is required and biofuels need to proof a fixed GHG reduction potential in relation to a fossil reference. There always exists the possibility to calculate GHG emissions based on actual production values, in accordance with EU RED methodology.

Since the EU default value of soy biodiesel (31%), based on soybean cultivation and transport from Brazil to Europe, fails the EU RED 35% GHG mitigation target USB – using most recent agriculture and processing data – has recalculated GHG emissions of soy biodiesel in conformity with EU RED methodology (Annex V Part C of Ref. [11]) [52]. As the USB study of Ref. [46] (*cf.* Section 4.1) used mass allocation, the model was recalculated using energy allocation percentages, conform the EC approach. In comparison to previous data [28] reductions of 45% and 35% were introduced for crushing and transesterification, respectively. The GHG emission savings following EC methodology were re-evaluated in various ways:

– Scenario 1: Substitution of (updated) US soybean agriculture data for Brazilian data and transport of US soybeans to Europe for conversion into biodiesel. The GHG reduction factor is

calculated using the European emission factor (EF) for petroleum diesel (83.8 g CO_2 eq/MJ diesel). With GWP of 606 g CO_2 eq/kg from cultivation and harvesting soybeans and the biodiesel energy content of 37.2 MJ/kg a value of 16.3 g CO_2 eq/MJ is derived for the US cultivation phase, *i.e.* a reduction of about 3 g CO_2 eq/MJ compared to Brazilian soybean production. Transportation from US to Europe contributes 21% of total emissions and represents a GWP of about 330 g CO_2 eq/kg or 8.9 g CO_2 eq/MJ; *cf.* approximately 13 g CO_2 eq/MJ for Brazil to Europe, which reflects the larger distance.

- Scenario 2: Substitution of Brazilian soybean agriculture data with US data and European processing data with US data and transport of finished biodiesel to Europe. In conditions of US soybean processing and biodiesel production the final GHG emission values for the processing steps are 2 to 4 g CO_2 eq/MJ below RED figures. Transportation results in more than 50% reduction as compared to scenario 1 where several kilograms of soybeans were transported to produce one kg of biodiesel in the EU.
- Scenario 3: Use of the US emission factor (EF) instead of the European EF (*cf.* Table 28). The EF value is a critical parameter in determining final GHG reduction percentages. Since the US EF is higher than the EU factor the former improves the overall GHG emission reductions for soy biodiesel. The results of this sensitivity analysis show that the GHG reductions of each of these scenarios do exceed the 35% minimum requirement, even when using the default values, and can range to almost 60% depending on the option selected (Table 29).

Using recent US soybean production and processing data and transportation to EU from US instead of Brazil results in higher GHG emission reduction values, ranging from 39% to 56% depending on the scenario tested. The new data eliminate the need to use default data with the 40% multiplication factor. Table 29 shows that substitution of actual operating data for soybean processing instead of default GHG emission data has the greatest impact on the final GHG emission savings results. US soy biodiesel meets the EU minimum emission target.

UFOP (Union zur Förderung von Oel- und Proteinpflanzen e.V.) has promoted a review of the recent USB life-cycle impact of US soybean and its industrial products [46] and conformity to EU RED [52]. Table 20 compares yield and input data for soybean production according to USB [46], EU RED [11] and the Ecoinvent database [151]. Data reported by USB are very similar to the background data of the EU RED default value. It is noticed, however, that the USB study underestimates the environmental impact of nitrogen as the BNF contribution has not been considered explicitly (*cf.* Table 20).

Table 30 compares data reported for soy crude oil production. Only the values for steam and hexane differ significantly. Moreover, Table 31 denotes strong differences for the transesterification stage. In particular, the demand of steam within the USB study is below the default value of EU RED. Methanol consumption is clearly underestimated and should be at least 99.7 kg for conversion of 997 kg crude oil. The observed substantial differences in assumed process data between USB and EU RED, in particular as to field emissions and demand of steam, have a considerable effect on the overall soy biodiesel GHG balance.

USB has required to examine the calculated values and to adapt the default value if necessary. The German Biomass Research Centre (DBFZ, Leipzig) has examined whether the USB results [46,52] are suitable for an update of the EU default value of soy

Table 28
Fossil diesel emission factor (EF).

	Unit	EU	USA
Emission diesel production	g CO_2 eq/kg	382	663
Emission diesel combustion	g CO_2 eq/kg	3204	3182
Total emission	g CO_2 eq/kg	3587	3845
Fossil diesel energy content	MJ/kg	42.8	43.5
Petroleum diesel EF	g CO_2 eq/kg	83.8	88.4

Table 29
GHG emissions for US soybean (different scenarios) in comparison to EU RED.

GHG emission scenario	(g CO_2 eq/MJ)				GHG savings[a] (%)
	Cultivation	Processing	Transport/ distribution	Total	
EU RED typical[b,c]	19	18	13	50	40
EU RED default[b,c]	19	26	13	58	31
US Scenario 1 typical	16	18	8.9	43	48 (51)
US Scenario 1 default	16	26	8.9	51	39 (42)
US Scenario 2 typical	16	16	4.7	37	56 (58)
US Scenario 2 default	16	22	4.7	43	49 (51)

After Ref. [52].
[a] With respect to EU petroleum diesel EF value of 83.8 g CO_2 eq/MJ. In parenthesis comparis onto USEF value of 88.4 g CO_2 eq/MJ.
[b] Typical/default GHG emissions.
[c] Based on cultivation in Brazil, soybean export to Europe and processing in EU.

Table 30
Comparison of crude soy oil production data.

Process value	Unit	USB [46]	EU RED	Ecoinvent US
Inputs[a]				
Electricity	kW h	289	319	299
Steam	MJ	6290	5319	5202
Soybeans	kg	5236	5319	5316
Hexane	kg	2.96	3.72	11.16
Outputs				
Soymeal	kg	4131	4319	4221
Crude soy oil	kg	1000	1000	1000

After Ref. [154].
[a] Inputs per 1000 kg soy oil.

Table 31
Soy biodiesel production data.[a]

Process value	Unit	USB [46][b]	EU RED	Ecoinvent US
Inputs[c]				
Soy oil[d]	kg	997	1019	1027
Electricity	kW h	36	35	42
Steam	MJ	874	2856	920
Methanol	kg	91.65	109	113.16
Other chemicals[e]	kg	69.375	31.2	5.73
Outputs				
Biodiesel	kg	1000	1000	1000
Glycerin	kg	120	106	83

After Ref. [154].
[a] Unallocated data.
[b] Reflects US biodiesel plants including plants using canola oil.
[c] Per 1000 kg soy biodiesel.
[d] General feedstock (refined, crude or degummed crude oil).
[e] Sodium methylate, sodium hydroxide, hydrochloric acid, phosphoric acid, citric acid, sodium carbonate.

biodiesel or whether it is possible to establish a specific default value for US soybean production [154]. For the calculation of GHG emissions all emissions and expenditures were considered from the production and use of fertiliser, seeds, diesel fuel and pesticides (soybean production stage), use of electricity, steam, hexane, methanol, *etc.* (soy oil production and conversion stages) and distribution [52]. In order to enable comparison system boundaries for USB and EU RED (well-to-wheels), consideration of by-products (allocation based on lower heating value), N_2O emissions (IPCC 2006), functional unit (1 MJ), and of infrastructural expenditures (not considered), were taken identical. Fossil fuel energy content of 42.8 MJ/kg, biodiesel fuel energy content (37.2 MJ/kg) and EU fossil fuel emission factor (EF) of 83.8 g CO_2 eq/MJ were used. The base data for calculation of GHG emissions for US soy biodiesel production are given by Ref. [46]. With 16 g CO_2 eq/MJ the GHG value for cultivation is about 15% under the EU RED default value as a result of lower fertiliser application (*cf.* Table 30) and assumed field emissions (350 kg N_2O/1000 kg soybeans).

The USB study evaluated various scenarios [52]. Clearly, GHG emissions caused by overseas transport from US to Europe (6350 km) are reduced as compared to shipment from Brazil (10,186 km). Although in scenario 2 a GHG mitigation potential of 56% is obtained (Table 29), which exceeds the 35% savings potential required in EU RED, some of the background data of Ref. [46] requires further examination. In particular, methanol consumption is underestimated. A scenario based on use of the US emission factor for fossil fuels (EF=88.4 g CO_2 eq/MJ) for calculation of the GHG mitigation potential is not in compliance with EU RED guidelines. It has been concluded that biodiesel produced from US soybeans is capable of reducing GHGs by 56% when standard production values are employed [154].

Argentina has challenged both US and EU regulations. In mid-2009 Argentina has presented comments to EPA's Regulations of Fuels and Fuel Additives, and the changes to the US Renewable Fuels Standard (RSF2). It was shown that Argentine soy biodiesel reduces GHG emissions for more than the established minimum level of 22%. EPA currently recognises that Argentine soy biodiesel meets the 50% reduction in GHG emissions and qualifies for the biomass-based diesel category. Argentina has also challenged EU's 35% minimum GHG emission savings ruling. INTA has drawn attention to the country's extensive adoption of no-till cropping, the short transport distances from farms to crushing, processing and port facilities, and its modern industrial infrastructure. INTA has also verified the status of areas cultivated before 1 January 2008, in compliance with the EU Directive (GO areas). Moreover, the Argentine Chamber of Biodiesel (CARBIO) has presented the EU a voluntary certification scheme addressing all their requirements. This scheme has been recognised by the European Commission.

EU Directives 98/70/EC and 2009/28/EC (RED) include sustainability criteria including minimum GHG saving thresholds, but do not consider changes in the carbon stock of land resulting from indirect changes in land use. The European Union is reviewing its policy options for the biofuels sector and recently proposals for amending both Directives have been formulated [216]. In particular:

- the 2020 biofuels for road transport target of 10% is maintained but restructured by restricting the contribution of conventional biofuels (obtained from food crops) to their share ($<5\%$) in consumption level of 2011 and by giving more emphasis to second-generation biofuels;
- the minimum required GHG emission savings threshold of 60% for new installations is brought forward in time (with effect from 1st July 2014); existing installations shall achieve GHG savings of at least 35% until 31 December 2017 and at least 50% as from 1 January 2018;
- in the calculation of GHG emission savings land use (as crop production) is now included explicitly;
- calculation of GHG savings is simplified;
- crop-specific ILUC factors have been introduced (55 g CO_2 eq/MJ for oilcrops); and
- equal treatment will be reserved for producers regardless of the location of production.

Equal treatment for producers implies that while third countries are allowed to use default values, EU producers are required to use actual values where they are higher than the default values. Bringing forward of the GHG threshold does not address indirect land-use change but by requiring a better GHG performance the chances are greater that the total of direct and indirect GHG emissions will be lower than the fossil fuel comparator. The extent to which direct emission savings are required depend on the fossil comparator and the GHG default values. Raising the fossil fuel comparator from the current 83.8 g CO_2 eq/MJ to 90.3 g CO_2 eq/MJ increases the direct emissions savings of biodiesel feedstocks and equals a lowering of thresholds with 8.4%. Lowering the direct GHG default emission values decreases the need to achieve further direct emissions savings. The fossil fuel comparator has not been raised [216]. Soy and rape biodiesel will have difficulties in meeting the threshold of 60% or even 65%. In the case of soy, already the increase to 50%, as laid down in the current RED and FQD, is difficult to achieve.

The weighing of advanced biofuels towards the 10% RED target is increased compared to conventional biofuels. The energy content of biofuels with particularly good GHG emission balance performance levels (such as those based on waste vegetable oil and animal fats) count double for the purpose of compliance with the 10% target. Biofuels made from feedstocks that do not lead to additional demand for land, such as those from waste feedstocks, are assigned a zero emission factor. Advanced and sustainable biofuels from feedstock (*e.g.* algae) that do not create an additional demand for land are favoured. The sustainability criteria are waved for some of these products.

The new methodology for calculation of GHG emissions from the production and use of transport biofuels, which now takes into account the productivity of the crop (measured as biofuel or energy per unit area per year) is unfavourable for soy biodiesel. In practice, the new EU proposal limits the contribution that soy biodiesel can make towards the attainment of the RED targets.

Introduction of ILUC factors is another considerable challenge for the EU biodiesel sector. As the 2020 targets to achieve 10% renewables in transport and 6% GHG reduction from fossil biofuels will not be affected by ILUC policy, the EU 2020 demand for biofuels will not change (actually diminishes in view of multiple countings). The EU biodiesel industry will face a decrease in demand as a result of introduction of ILUC factors. It will also be more difficult to supply conventional biodiesel to the EU market.

Rather than having GHG savings numbers for different geographical areas, EC prefers differentiated GHG numbers based on specific pathways, *e.g.* no-till farming. No new GHG savings numbers will be introduced until the question of ILUC is solved. Investments in installations with low GHG savings performance is to be discouraged. Existing investments will be protected until 2020. It is expected that in 2014 some 80% of current EU biodiesel installations will need such protection [217].

At present, biofuels consumption in transport in EU (14 Mtoe in 2011) is almost in line with the National Renewable Energy Action Plans (14 Mtoe in 2010), which project biodiesel consumption of 14,542 ktoe by 2015 and 21,649 ktoe by 2020 [206]. There is confidence that these targets will be met. Prospects for first-generation biodiesel development in Europe are limited by the dearth of dedicated farming land and the trends in global demand.

Is seems best to focus production of biodiesel on feedstocks that are decoupled from the global food and feed markets, such as use of non-edible energy crops that grow specifically on degraded land. This conforms to the conclusion expressed in the Gallagher review [17].

5.3.1. Land-use effects

Apart from the sustainability required of minimum GHG emissions savings EU RED has placed restrictions on the types of land that may be converted to production of biofuels feedstock crops: (i) no conversion of land with high carbon stock since January 2008 (wetlands, continuously forested areas, peatlands); (ii) no raw material from land that had high biodiversity value as from January 2008 (primary forest, biodiverse grassland, nature protection areas). The Argentine CARBIO Sustainability Certification Scheme (CSCS) – and others – has specifically been developed to demonstrate conformity with EU RED.

Land use is seldom taken into account in LCAs (but see Refs. [4,38,63]) since there are no impact assessment methods available. However, in agricultural production, land use is one of the most significant impact categories. There is an urgent need to work out methods for impact assessment of land use. Mattsson et al. [66] have formulated various impact sub-categories under the land-use category, in particular soil fertility, biodiversity and landscape value (*cf.* Section 5.2.3).

Arable land is a constrained production factor in many countries. The production of biodiesel is land intensive. Other forms of land use are supply of food, production of biomaterials and nature conservation. Assessment of the total environmental impacts of producing biodiesel thus needs to consider also indirect impacts, *i.e.* beyond the biodiesel value chain. The soybean cultivation area is high in comparison to other major oilcrops: soy 102.56 Mha, oil palm 15.41 Mha, rapeseed 31.64 Mha, sunflower 23.11 Mha (2010). Land occupation for rape cultivation is lower than for soybeans due to higher yields. Oil palm is world's most efficient bearing crop in terms of land utilisation, efficiency and productivity.

Arable land occupation for soybean cultivation is the main source contributing to the land-use (LU) impacts. Results for Argentina are similar to US values, as most of the soybean (64% for Argentina) is cultivated as first-class soybean. A pathway modelled as a second-class soybean (as in Brazil) results in lower land occupancy but also in lower hectare yield (*cf.* Table 12). Obviously, the fossil reference performs better than biodiesel pathways.

Additional feedstock production affects land use. Biofuels should not be made from raw materials produced on land with high carbon stocks. During the 2008–2020 period significant land-use changes, *i.e.* area(s) transformed (land type and geographical location) as a result of crop consumption in a given region, will take place driven by additional food demand and non-food use (biofuels mandates). The question how an expanding bioenergy sector will interact with other land uses, such as food production, biodiversity, soil and nature conservation, and carbon sequestration, has been analysed insufficiently. Close attention needs to be paid to the economics of scarce land resources and the competition for land between food and energy crop production under stringest CO_2 carbon policies. A framework for LCI modelling of land-use changes induced by crop consumption has been proposed [67].

While land-use change (LUC) is not an inherent biodiesel property, it certainly is the most controversial and uncertain issue associated with biofuels [135]. Direct LUC (DLUC) occurs if previously uncultivated land is used to produce biomass feedstocks. Typical DLUC scenarios are improved grassland, and low- or full-tillage cropland converted to soybean cultivation. GHG emissions from clearance and conversion may be significant for converted land with a high carbon stock (now EU RED restricted). Indirect LUC (ILUC) is associated with the displacement of an existing agricultural activity. The indirect land-use change of biofuels is the direct land-use change of another commodity. The most critical questions revolve around indirect land-use. In order to assess more accurately biodiesel production pathways, further consideration should be given to include ILUC. For example, US soybean is produced in rotation with corn. Consequently, increased corn acreage in US will reduce soybean production and increase soybean price. The LCA community (*e.g.* EPA *vs* CARB) is yet to come to consensus on a methodology to incorporate indirect land-use in LCA and life-cycle carbon emissions [218]. Currently, only the US EPA considers indirect LUC [36].

Production of a specific crop may be enhanced by displacement of other crops (to be compensated for by production elsewhere), expansion of croplands or intensification of existing production [67]. Increases in cropping intensity and yield growth per hectare (intensification) reduce the need for cropland expansion. Intensification can be achieved through optimisation (application of fertilisers, pesticides and irrigation) or technical development (improved mechanical aids, agricultural practices and higher yielding crop strains). Optimisation of production is subject to diminishing returns: the higher the level of fertilisers, pesticides or irrigation, the lower the yield increase per unit of input (situation in development countries). Moreover, legal restrictions on the use of agrochemicals may apply [219]. Displacement is constrained by climatic conditions, soil properties and crop rotation schemes. Displacement embodies the fuel *vs.* food/feed controversy.

As demand for agricultural commodities is growing, part of that additional demand will be met through an increase in world arable land (presently *ca.* 1555 Mha cropland, FAOSTAT 2007). Overall exploited land is forecasted to increase by 0.25 to 1.4%. Expansion of croplands – with high marginal costs – typically takes place at the expense of nature, but may also occur on land already transformed. Agricultural opportunities in highly populated areas are restricted. The global agricultural land use of the EU already exceeds its domestic agricultural land by 20% [220]. In recent years, croplands in Europe and USA have been contracting by 1.7% and 1.1%, respectively. On the other hand, other areas (Argentina, Brazil and Canada) show fewer agricultural restrictions. Lapola et al. [136] have modelled land-use changes arising from the fulfilment of Brazil's biofuel targets for 2020 concurrent with increasing food and livestock demands. The expansion of soybean plantations in response to increased biodiesel production is expected to occur mainly in the central states (MT, MS, GO, MG). To comply with the Brazilian production targets for 2020, soybean (with a potential yield increase of 0.8 t/ha) would require an additional 10.8 Mha, mostly replacing rangeland. Food cropland area replaced by biofuels would reach 1.43 Mha. Direct deforestation caused by soy biodiesel would amount to only 180 kha of forest and 200 kha of woody savannah [136].

With increasing demands for biofuels feedstocks it is important to know how much of the demand is met by additional production and how much is displaced by other uses. Expectations are that more than 80% of increased production of key oilseeds and sugar crops will come from extensification (additional land) rather than from intensification (higher yields).

The land requirement for biodiesel production varies considerably for different oilseeds due to different crop yields and oil content. Soybean is at the lower end of the biodiesel/ha scale (about 450 L/ha). The vast differences in yields between different types of land make an estimate of the additional arable land needed to reach biofuels targets difficult. Ecofys has quoted a 4.9 Mha of land-use change extra-EU to meet a 7% energy target

[221]. Typical yields of expanded (usually less fertile) land are below average.

Agricultural products are subject to international trade, and consequently, the geographical scope is global. While feedstock (or biodiesel) can be imported into the EU, this will raise costs and contribute to transport energy consumption and emissions. Globally, production is shifting from developed countries (with high input levels) to emerging countries using less intensive techniques and reduced average use of fertilisers.

In case of South America (and S.E. Asia) the impacts related to the transformation of land are of more concern than those from continuous cultivation. There are significant differences between the impacts from transformation of 1 ha of different land-use types into agricultural land in various regions (Table 32); *cf.* also Table 35. The impact on biodiversity by transformation of primary forests into intensive agriculture is considerably higher than in case of degraded/secondary forests. Logging is the determining activity in transforming primary forests into degraded/secondary forests. The disappearance rate of primary forests in Brazil and Indonesia in the years 2000 to 2005 has been three to four times faster than the expansion of agricultural land [222,223]. The impacts from such transformations cannot be ignored.

The agricultural phase in Argentine and Brazilian biodiesel pathways performs similarly with respect to CED and GWP. When land change occurs, the provision of land accounts for a significant part of the impact [3,38,67,82,116,135]. The high impact factors of Brazilian and Argentinean soybeans are mainly due to emissions from land-use change. After the 2006 soy moratorium was implemented most of Brazil's soybean expansion in the Amazon region has occurred on land previously used as rangeland [224]. However, this shift of rangeland by soybean leads to migration of cattle ranchers closer to the deforestation frontier [225–227]. The efficacy of biofuels in Brazil can be considerably compromised if biofuel-related ILUC takes places [207]. For effective carbon savings from biofuels in Brazil closer collaboration between the biofuels and cattle-ranching sectors is crucial [136]. The adverse impacts of (indirect) land-use change need to be mitigated *before* stimulating large-scale supply of biodiesel [64]. This requires screening of feedstocks for conditions of production with positive environmental and social impact management (*e.g.* soy conforming to RTRS), certification, verification and control, as well as enforcement.

The European Union (EU) recognises that various uncertainties associated with indirect land-use change (ILUC) modelling remain to be addressed, which could significantly impact the outcome of biodiesel LCA studies [228]. Consequences of total land-use change – direct and indirect – of the European biofuels policy have been assessed for a mandate leading to an increase in global cropland area of almost 1.8 Mha [196]. It should be remembered that many more countries have mandates in place (*cf.* Section 5.3). Consequently, the total global land area requirements for biofuels are much higher. The most affected regions in terms of cropland extension are considered being in Latin America. Sources of extension of cropland worldwide are quoted as pasture (42.8%), managed forest (37.4%), followed by savannah and grassland, including the Brazilian Cerrado (16.4%), and finally primary forest (3.4%), *i.e.* almost 80% within managed land (pasture and managed forest) [196].

Table 32
Effects of transformation of different land-use types into agricultural land for soybean cropping in Brazil.

	Savannah	Grassland	Rainforest	Sec. forest
GWP (t CO_2 eq/ha)	303	125	679	796
Biodiversity (wS100/ha)	928	n.a.	n.a.	538

After Refs. [65,155].
n.a., not available.

The largest potential for expanding EU agricultural production for biodiesel would be to increase the arable area at the expense of grazing land. However, ploughing up grassland has serious GHG consequences. The change in land-use results in a reduction in the organic carbon stored in the soil (*cf.* Table 33). The carbon release would negate GHG savings of biofuels for many decades. Similar considerations hold for other land categories. Currently, government aspirations for biofuels production exceed the levels that can be produced on arable land. Reconversion of grazing or forestland is counter-productive in terms of GHG reductions. The Gallagher review to RFA [17] suggests that no future bioenergy crops should be cultivated on agricultural land since this may displace food crops to pristine environments where other ecosystem services could be threatened. Idle or marginal lands should be used instead. Idle land is defined as former or current agricultural land that will not otherwise be used for food production; and land potentiality suitable for agricultural production. Marginal or degraded land is land with poor soils or harsh environments (unsuited for food production) or areas degraded through deforestation.

It is not unreasonable to suppose that the problem of land scarcity will be alleviated by future biomass-based technologies which make use of the entire plant rather than just the oil-rich parts of oilcrops. The use of lignocellulosic biomass and algae will relieve the pressure on farming land.

5.3.2. *Impact of land-use changes on GHG balances*

Biodiesel has the potential to reduce GHG emissions if land-use change can be avoided. The main factor is the way energy crops are cultivated. Among the many environmental impacts of biodiesel production land-use change (LUC), which greatly influences the extent to which biofuels contribute to the mitigation of GHG emissions, is prominent. GHG emissions for land-use changes to cropland are based primarily on the difference between the carbon stocks present in standing biomass and the time-averaged soil carbon of farmed land. This differencing method estimates CO_2 emissions associated with changes in biomass, but CO_2 emissions also occur from soil when land is tilled and used as annual cropland. Carbon stocks vary considerably among different land cover types and different geographic regions. Table 33 illustrates the substantial variation in carbon stock estimates for different land types in Brazil.

GHG emissions from land-use change vary widely between biomes and specific locations but typically stem from aboveground

Table 33
Average carbon stocks (Mg/ha) for land categories within Brazil.

Land categories	Aboveground carbon	Soil carbon
Tropical forest	198	69
Woody savannah	34	52
Grassland savannah[a]	6	71
Typical savannah[b]	24	45
Sugarcane cropland[c]	17	43
Cultivated pasture[d]	4	52
Soybean cropland	1	52
Sugarcane cropland[e]	17	34
Corn/maize cropland	3	40
Degraded pasture	<1	40

After Ref. [229].
[a] Campo limpo.
[b] Cerrado.
[c] Unburned.
[d] Managed.
[e] Burned.

carbon in forest, savannahs and wetlands and from belowground carbon retained in the soil and roots of temperate grasslands. Idle land, such as set-aside, accumulates carbon in the soil over time, which is generally released when the land is brought back to agricultural production by ploughing. GHG savings will therefore be better where biofuels are grown on rotational rather than permanent set-aside or fallow land. Some agricultural practices preserve soil carbon, for instance through avoiding excessive tillage. Careful agricultural practices offer opportunities for net GHG savings from use of idle land. The effects of displaced agricultural activity and resulting land-use change on the potential GHG benefits of biodiesel need careful assessment.

Using worst-case DfT default values GHG savings for selected biodiesel type (except for used cooking oil) under different land-use change assumptions are largely unsatisfactory, relative to RTFO thresholds [230], *cf.* Table 34. Table 34 indicates that previous land-use is absolutely critical in substantiating GHG savings. In most cases, savings are only possible if existing cropland is used, which means direct and undesired food-fuel competition. Bringing permanent grassland or uncultivated land into arable use has longer term negative implications for GHG balances. Carbon emissions as a result of DLUC would originate mainly from soil carbon losses when converting rangeland to soybean plantations. Such DLUC carbon emissions require a payback time of at least 35 years, primarily because of the small annual hectare carbon savings from soybean biodiesel [136]. Biofuels feedstocks should not be grown on land where carbon losses arising from its cultivation require a payback time longer than 10 years [17]. Table 32 illustrates the CO_2 emissions related to LUC for marginal land types in Brazil taking account of the change in aboveground biomass, dead organic matter and soil organic carbon [65]. The emissions are related to a time horizon of 20 years.

Direct land-use changes generally have a small impact on carbon emissions because most biofuel plantations replace rangeland areas. However, indirect land-use changes, such as those pushing the rangeland frontier into the Amazonian forest, can offset the carbon savings from biofuels. There is much debate regarding the impact of increased soy production on deforestation. Serious concerns have been expressed about the negative environmental impacts of the unintended consequences of biofuels production, particularly the indirect land-use change (ILUC) impact of releasing more carbon emissions as forests and pristine lands are converted to cropland due to biofuel expansion [136].

ILUC is a phenomenon that is impossible to directly observe or measure. In other words, estimated land-use change can never be validated. Although the scale of effects of ILUC is uncertain the effect can potentially lead to a significant net increase in emissions and reduces or even totally eliminates the GHG benefits of biodiesel. The global nature of the indirect effects is complex. Quantification of GHG emissions from land-use change requires knowledge on the type of crop that has been displaced, the type of land-use change that occurs as a consequence of the displaced crop, and the amount of carbon released arising from land-use change. The carbon emissions from land-use change need to be included in the overall GHG emissions for evaluation of the sustainability of a specific biofuel. The limited availability of low-carbon stock land in other parts of the world and the lack of more stringent protection of forests and carbon rich areas are factors that can contribute to damaging indirect land-use change.

Table 34
GHG savings for biodiesel types under different land-use change assumptions.[a]

Biodiesel type	% GHG savings by conversion from		
	Cropland	Grassland	Forestland
Soy (Brazil)	9	−699	−2550
Soy (Argentina)	44	−109	−1134
UCO (UK)	85	85	85

After Ref. [64].

[a] Based on DfT (UK Department for Transport) default values.

Soybean biodiesel is expected to contribute to about 6 Mha of indirect deforestation by 2020, creating a huge carbon debt. Indirect land-use changes (ILUCs) would considerably compromise the GHG savings from growing biofuels, mainly by pushing the rangeland frontier into the Amazon frontier and Brazilian Cerrado savannah. Soybean biodiesel is held responsible for 59% of the indirect deforestation. Payback time for total LUC (DLUC+ILUC) for soybean is 246 years [136]. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. Oil palm would cause much less land-use changes and carbon debt.

Deforestation of dry subtropical forest in Argentina and Amazonian deforestation for soybean cultivation in Brazil significantly contribute to an increase in GHG emissions. When the effects of alternative land-use strategies on carbon stores are considered, most biofuels lead to a net increase in GHG emissions when compared to gasoline or diesel. Emissions due to preparation for agricultural use together with carbon stock changes due to land-use change represent 70% and 77% of the GWP of the feedstock production process in case of Brazil and Argentina, respectively [38]. Ill-sourced biodiesel can cause massive GHG emissions (*cf.* Table 34).

Although many studies have addressed various aspects of soy cultivation systems for biodiesel production in Latin America [4,38,41,63,79,231] only a small number has accounted for LUC [4,38,63–65]. Indirect LUC emissions have not yet been addressed. Castanheira et al. [63] have assessed the implications of different cultivation systems and direct land-use change (DLUC) on the life-cycle GHG balance of soybeans produced in Brazil and Argentina and exported to Portugal (with transport distances of 8145 and 9555 km, respectively). The various systems differ considerably in the type and quantities of fertilisers; no-tillage requires more pesticides. NT systems generally use less diesel, since direct seeding is mostly performed without primary tillage. LUC dominates life-cycle GHG emissions, with considerable variations for the previous land use (tropical forest, forest plantations, perennial crops plantations, savannahs and grasslands), soil types (low and high activity clay soils) and soil management practices (tillage, reduced- and no-tillage) in different climatic conditions (tropical moist, warm temperature moist and dry). The scenarios assessed (20 in Brazil and 15 in Argentina) show a huge variation in GHG emissions, from 0.1 kg CO_2 eq/kg soybeans (for NT production in previous degraded grassland, Argentina) to 16.5 kg CO_2 eq/kg soybeans (for production with tillage in previous tropical rainforest, Central West Brazil) (Table 35). In 24 scenarios GHG emissions due to LUC accounted for more than 80%, and only in 4 scenarios (all referring to conversion of severely degraded grassland) for less than 43%. All the tillage systems have higher GHG emissions than corresponding no- (or reduced-) tillage systems. GHG emissions in Argentina are lower than for the corresponding Brazilian scenarios, mainly due to lower cultivation emissions from fertiliser use but also due to reduced emissions from domestic transport (394 *vs* 790 km). Cultivation is responsible for 46 to 51% of total emissions. Direct emissions represent 62–79% of total agricultural emissions. Relatively low GHG emissions (<3 kg CO_2 eq/kg) are observed for conversion of grassland into soybean plantation (no-tillage), with the lowest values (0.1–0.5 kg CO_2 eq/kg soybeans) for severely degraded grasslands in Argentina, due to an increase in SOC of soybean plantation relative to SOC of severely degraded grassland. Clearly, the original land choice is a critical issue to assure the sustainability of soybean production and degraded grassland is a preferred choice for

Table 35
Life-cycle GHG emissions (kg CO_2 eq/kg soybeans) of soybeans produced in Brazil and Argentina in alternative LUC scenarios and soil management practices, and transported to Portugal.

Region	Previous land use	Soil management practice[a]	GHG emissions
Central-West Brazil	Tropical rainforest	T	16.5
	Forest plantation	NT	5.6
	Moderately degraded shrubland (savannah)	T	5.9
	Severely degraded shrubland (savannah)	NT	4.25
Southern Brazil	Forest plantation	NT	3.3
	Perennial crop	NT	5.3
	Moderately degraded grassland	T	1.5
	Severely degraded grassland	T	6.2
Argentina	Forest plantation	RT	2.9
	Perennial crop	RT	3.9
	Severely degraded grassland	NT	0.1

After Ref. [63].
[a] NT, no-tillage; RT, reduced tillage; T, tillage.

soybean cultivation. When the effect of alternative land-use strategies on carbon stores are considered, most biofuels lead to a net increase in GHG emissions when compared to gasoline or diesel.

The prospects of marginal to large-scale biodiesel production increases requires extensive modelling of the interactions between bioenergy, food and materials production (competition for resources), biodiversity, soil and nature conservation. Various EU-initiated studies have evaluated the environmental consequences of global land-use change as a result of the realisation of the renewed 2020 biofuel targets in terms of GHG emissions [196,197,228,232–236]. Most of the modelled scenarios project that the largest share of LUC for biodiesel will occur outside the EU. ILUC impacts depend strongly on base assumptions in modelling, including yields, food/feed consumption, land classification, carbon stock values, and geographical origin of the feedstock. Different assumptions have been made as to the total share of biofuels for road transport by 2020 (up to 8.6% in energy), the amount of advanced biofuels (up to 1.5%), as well as the biodiesel/bioethanol ratio (from 83/17 to 55/45). An ILUC factor is a quantity of g CO_2 eq/MJ added to the crop-specific life-cycle GHG emissions that reflects GHG emissions associated with land use. ILUC emission coefficients increase with the size of the mandate and rapidly erode the environmental sustainability of most first-generation biofuels.

Laborde has assessed land-use change consequences of the European biofuels policy assuming consumption of 27.2 Mtoe 1st generation biofuels (biodiesel/bioethanol in 72/28 ratio) by 2020 (or 86% of target), which requires a 15.5 Mtoe additional mandate [196]. Land emissions over a 20 year period, induced by the full EU biofuels mandate are about 39.1 g CO_2 eq/MJ biofuels, or 34.5 g CO_2 eq/MJ for half mandate. Total amount of emissions is 500 Mt CO_2. LUC emission coefficients at the mandate level for biodiesel and bioethanol feedstocks are on average 54.3 g CO_2 eq/MJ and 11.1 g CO_2 eq/MJ, respectively. Differences in LUC emissions for oilseeds are small (Table 23). Soybean shows the highest emission coefficient. LUC emissions are reduced by only about 12% for half mandate [196].

As shown in Table 23, with improved technology and yields all biofuels qualify for the EU sustainability scheme that requires direct savings of at least 45 g CO_2 eq/MJ or 50% of fossil fuel emissions. On the basis of 2020 technology (*i.e.* new plants) with annual direct savings of 57 g CO_2 eq/MJ (20 years) and annual LUC emissions of 38 g CO_2/MJ net emission savings of 19 g CO_2 eq/MJ of biofuels consumption are calculated for the additional EU mandate. In other words, land-use change emissions prevail over direct emissions of methane and nitrous oxide from agricultural systems and cancel almost two-thirds of the total direct emission savings for the entire EU biofuels mandate. The overall mandate will thus not achieve the intended savings of over 50% compared to fossil fuels.

Malins has reported the most recent update of modelling of ILUC emissions from the additional EU biofuels mandate (biodiesel/bioethanol 72/28) [197]. Biodiesel from soybean, rapeseed and palm oil show negative savings when added ILUC is included, with sunflower being almost neutral. Only bioethanol has a positive savings potential of over 50%. An important constraint for biodiesel production as compared to bioethanol is its considerably greater need for land use. With the overwhelming effect of land-use changes it is doubtful that technological improvements for biodiesel production will ever be able to compensate the net emission losses.

Given the aforementioned uncertainty of the effects of indirect land-use change net GHG emissions from current biodiesel targets cannot be assessed with certainty. Consequently, there is the risk that biofuels targets lead to a net increase in GHG emissions. The largest potential for expanding EU agricultural production for biofuels would be to increase the arable area at the expense of grazing land. However, ploughing up grassland has very serious GHG consequences. The carbon release would wipe out GHG savings of biofuels for the short to medium term (many decades). Similar considerations hold for forest land. The EU is in the process to develop regulations to limit the impact of indirect land-use change. There is no consensus on how to account for indirect LUC emissions [228]. Current approaches to ILUC have been assessed [229].

A cause of concern of the biodiesel sector is the allowance made for the indirect land-use change impacts when calculation GHG emissions in relation to the sustainability criteria of EU RED. The recent proposal for a EU Directive [216] has defined crop-specific ILUC factors, namely 55 g CO_2 eq/MJ for oilcrops (*cf.* Section 5.3.1). This makes it more difficult for biofuels crops with high ILUC-risk to meet the required GHG savings. Low-ILUC risk biofuels, *i.e.* biofuels that are produced with a low risk of causing ILUC, include: (i) biofuels from wastes and residues; (ii) biofuels produced additionally from yield increase developments; (iii) biofuels produced additionally from integration of biofuel crop with livestock herding; and (iv) biofuels produced on degraded or used lands [217]. The biofuels industry opposes factoring in the ILUC effect on the basis that it cannot scientifically be measured and therefore depends on controversial hypotheses and models. ILUC emissions factors will be included in the sustainability scheme as of 1st January 2020.

According to RED, on the basis of the default value (31%) soy biodiesel does not automatically comply with the current GHG emission criteria (35%). However, soy biodiesel has a GHG saving exceeding the threshold if the typical value (40%) is used (supporting documentation needed). Starting in 2017, the GHG emission saving has to be 50%, which is difficult to meet for soybean. Focusing on the American production of soybeans and soybean oil-based biodiesel the American Soybean Association (ASA) claims a GHG emissions savings of 52% [237]. ILUC contributions complicate matters for Brazilian and Argentine soy biodiesel.

GHG emissions caused by indirect land-use changes should be minimised. When land for feedstock production is expanded in pristine environments (or even managed forest/pasture) it would have different consequences for different regions depending on their carbon stocks. The GHG emission criterion implies that direct use of carbon-rich lands is generally inappropriate for biodiesel. GHG savings are better where biocrops are grown on rotational

rather than permanent set-aside or fallow land [17]. Avoiding excessive tillage can also preserve soil carbon. Where feedstock production requires the dedicated use of land, a significant net gain in GHG emissions is likely only if the land is otherwise marginal from a carbon perspective. This means it neither sequesters significant storage nor produces significant food, yet it produces biofuel feedstocks abundantly. This typically implies land wet enough to support high plant growth but degraded and unproductive for other reasons. For lands with a low soil carbon content (*e.g.* which has been in use recently or has not been fallow for very long) good net GHG savings and relatively short payback periods are possible. Use of degraded grasslands or marginal lands for energy crop production could avoid impacts related to LUC and reduce GHG emissions. It has been estimated that the human food market increases the LUC effect by 15–20% for most oilseeds [196].

5.3.3. Biofuel policy issues

The most significant demand driver for soybeans is the animal feed market but biofuel policy plays an important role in defining use of the soy oil co-product. The two markets are interrelated.

The LUC effect cancels the environmental benefit of the EU biodiesel (mainly rape biodiesel) policy [196]. Similarly, Brazil's planned large increase in the production of biofuels in the next decade potentially leads to both direct and indirect land-use effects which can overcome the carbon savings from such biofuels [136]. Also Argentina's large-scale soy biodiesel initiative is only sustainable in energetic and environmental terms – not to mention other aspects – if no deforestation takes place, needed to allow even larger-scale production [38]. These observations call for a general mitigation strategy, as recognised recently by the EU [216]. As ethanol carries considerable lower risk of land-use emissions than biodiesel benefits could be derived from a more equilibrated bioethanol/biodiesel ratio.

The biofuels policies increase the price of energy contents in crops (oils and sugar) but lead to a relative reduction of the price of proteins (meal). The policy provides a premium to oils and fats. The biofuels policy causes the relative prices to change and therefore reallocates production. Low-carbon fuel policies such as the Renewable Energy Directive (RED), UK's Renewable Transport Fuel Obligation (RTFO), as well as initiatives of the California Air Resources Board (CARB) have included minimal sustainability criteria to govern the production of biofuels.

Large-scale use of biofuels and in particular biodiesel has lately increasingly been questioned. Many of the attributed benefits of biofuels have been re-examined. Production of almost 7.2 EJ of biofuels by 2020 would require almost 83 Mha (yielding on average 86 GJ/ha). Production of biodiesel from oilseeds is less favourable as 25 Mha are needed to produce just 0.75 EJ of biodiesel [220]. The International Energy Agency is particularly sceptic regarding the future of 1st generation biofuels such as soy biodiesel which can contribute to pressures on food supplies and have a relatively low potential for the reduction of GHG emissions. RTFO has envisaged a more cautious growth in the biodiesel market than EU RED.

Despite the EU's commitment to increase the share of renewable energies in transport, biofuels are among the most heavily taxed energy sources. Clean renewable fuels are being taxed at a higher rate than the heavily subsidised fossil fuels.

6. Conclusions

Soybeans are mostly being produced within modern, highly mechanised, industrial agricultural systems based on the use of genetically engineered seed varieties, chemical fertilisers, agrochemicals, industrial supplies and fossil energy. In the most favourable conditions, input (machinery, fertilisers, energy, *etc.*) cannot be decreased below certain limits. The balance then depends on outputs. The fossil energy and GHG savings of conventionally produced biodiesel are critically dependent on cultivation/manufacturing processes and the allocation of by-products. When energy gain and ratio are low a crop is not valid as an energy crop, but should find other use (food or feed). As shown by its best conditions (US pathway), a certain (limited) amount of soy oil is well invested in biodiesel use. However, biodiesel at large is not a cost-effective GHG abatement strategy [19] and the energy throughput per unit of labour of biodiesel is far from satisfactory [18]. There is also a fundamental trade-off between local and regional environmental impacts and global impacts.

Biodiesel, which is part of a low-carbon transport future, is a niche fuel with its production capacity being limited by land area constraints, not by energy inputs. As all products, biodiesel needs to be sustainable. Georeferenced LCAs and feedstock-specific biodiesel pathways assist in suggesting improvements in specific biodiesel pathways in order to comply with international sustainability criteria. More sustainable biodiesel production requires above all improving agricultural practices, in particular in South America and China. Brazil and Argentina need to avoid soil erosion and land-use changes, increase soil carbon stocks and use agrochemicals more carefully. China requires an overall more efficient agriculture and higher yielding crops before being able to meet US standards where the environmental impact of SME production has been decreased by use of higher yield soybean species, optimised fertiliser management, application of less toxic herbicides, improved crushing and oil refining practices, and use of fuel-efficient agricultural machinery. Advanced seed preservation technology can further reduce the total energy consumption. Biotechnology offers opportunities for reducing environmental impacts.

The use of SME instead of fossil diesel fuel produces both environmental advantages and disadvantages. Produced in limited quantities SME is beneficial with respect to energy conservation and reduces the greenhouse effect but scores low in terms of several environmental impacts, notably acidification and ecotoxicity. These unfavourable impacts are mainly on account of agriculture. Tropical agriculture is characterised by high use of pesticides, clear-cutting and loss of biodiversity, whereas moderate latitudes witness low crop yields, intensive fertiliser use and mechanical tilling. The environmental impacts can be reduced by appropriate measures. In scenarios of high biodiesel mandates soybean specific LCA results are overshadowed by crop LUC effects leading to higher emissions than petrodiesel [4,136]. In view of the overwhelming impact of ILUC contributions to the total GHG emissions legally imposed environmental sustainability targets can only be met by minimising land-use impacts (2nd generation biofuels) or by considerable reduction of *direct* emissions; for the latter, this survey has identified many options in the agricultural stage (except for the US pathways). Soybean can achieve net emissions savings if its processing technology is improved and direct savings increased as compared to fossil fuel. New, more energy efficient, technology may improve the overall life cycle of biodiesel production. Technological improvements range from new catalysts (heterogeneous, lipase) to process intensification, alternative reactor concepts and separation technologies, but all this comes at a price and impairs the profitability of the biodiesel business [180,238,239].

Biofuels should be promoted in a manner that encourages greater agricultural productivity and use of degraded land. Additional land use and biomass production for non-food purposes must be most efficient. Without corrective action the current international biofuels policies do not deliver the desired net GHG benefits. Renewable energy mandates should be revised

downward. A mitigation strategy for European biodiesel is necessary, as already outlined in the Gallagher review [17]. The clear hierarchy between bioethanol and biodiesel in terms of LUC emissions calls for a larger share of bioethanol in biofuels policies. Measures shifting demand from biodiesel to bioethanol have already been recommended [197]. This could be achieved by raising the *direct* GHG savings threshold. Introduction of an ILUC factor (opposed by the biofuels industry as being based on controversial models) renders soy biodiesel more difficult.

Biodiesel production is limited by land availability and soy's low oil content determines a high specific land-use requirement, which is penalised by recent EU metrics. Expanding agricultural energy production may lead to land-use conflicts with other land uses such as food production or the conservation of natural areas. For crops harvested from land already in production life-cycle GHG emissions savings of soy biodiesel are at best 56% as compared to diesel fuel. Converting intact ecosystems to production would result in reduced GHG savings or even net GHG release from biodiesel production. The original land choice is critical in assuring the sustainability of soybean production; previous degraded grassland is to be preferred for soybean cultivation. Any solution to improve biofuel yield without more emissions is welcome. Using technologies to increase yield (*e.g.* biotech) could mitigate the emissions linked to land-use changes by reducing the requirement of additional land. However, this is unlikely to deliver positive effects on land use already by 2020. Use of improved agricultural practices aiming at reducing emissions, *e.g.* increased no-tillage, may deliver the quickest improvements. However, in modern industrialised agriculture, mainly consisting of monocultures, production is strongly dependent on chemical inputs and high technology to ensure high crop yields. Most of these resources are dependent on the availability of non-renewable resources. Soy biodiesel would provide greater benefits if its biomass feedstock were produced with lower agricultural input (*i.e.* less energy and agrochemicals) on land with low agricultural value, and requires low-input energy to convert feedstock to biofuels.

The general finding that agriculture is the stage that uses the largest amount of input flows calls for careful reorganisation of cropping activities leading to improved practices and cleaner production. The real challenge lies in sustainable agriculture at the global level, *i.e*. implementation of low-carbon agriculture in the coming decades with good governance of scarce land resources. Local expansions of cultivated area on set-aside land are preferable to displacement of crops which are compensated for by increased agricultural production elsewhere. When the effect of alternative land-use strategies on carbon stores are considered, most biofuels lead to a net increase in GHG emissions when compared to gasoline or diesel.

Biofuels can potentially reduce greenhouse gases. However, important GHG emissions are generated during crop cultivation (planting, harvesting, transportation) and agrochemicals production. Soil organic carbon is converted into CO_2 with land-use change to cropping but soil N_2O emissions are probably the largest (and least well quantified) source of GHG emissions associated with bioenergy crop production [43,163]. Sustainable crop production largely depends on understanding the role of N fertilisation and optimal nitrogen nutrition. Agricultural N_2O emissions are extremely variable and depend on crop type, soil composition and weather conditions, and farming practices including type and application rate of fertilisers. Consequently, prediction of the rate of emission of N_2O from soil is fraught with considerable difficulties. Further work should be conducted concerning the nitrogen cycle.

LCA studies of soy biodiesel have estimated N_2O emissions mostly from calculations based on IPCC guidelines with disputed emission factors, and occasionally from measurements on individual fields [79]. The N_2O emission factors (the conversion rates from nitrogen in soil and water streams to N_2O emissions to the air) are subject to great uncertainties. While the emission factor associated with N fertilisers is uncertain, that associated with rhizobial nitrogen fixation is even more controversial. The biological fixation process has been removed from the IPCC N_2O inventory. Consequently, the effects of BNF in soybean cultivation on GWP have been ignored in most recent LCAs but should more properly be accounted for. Only in a few cases BNF has been quantified [38,41,115] or the soybean mass left in the field has explicitly been considered [44]. While there is little support for the use of an emission factor for BNF by legume crops equal to that for N fertiliser, the current standard more likely underestimates the BNF contribution of soybean cultivation to GHG emissions. Field N_2O emissions may even be underestimated significantly. In short, the N_2O contribution to GHG emissions is mostly not transparent.

Quantifying environmental and sustainability performance is clearly an arduous task. Where N_2O emissions are high (and depending on soil, fertiliser, BNF, weather, timing, *etc.*) with very high and uncertain error margins a reasonable estimate of GHG emissions savings is almost impossible and makes demonstrating compliance with EU GHG thresholds scientifically almost impossible. The GHG balance from agricultural activities is particularly uncertain [63] and the resulting error bars, if considered at all (not in LCAs!), are so high that it can be impossible to ascertain whether any pathway has a positive or negative GHG balance. Because of the very high greenhouse effect of N_2O (296 CO_2 eq) even relatively small emissions can have a significant impact on the overall GHG balance. Moreover, net GWP savings depend very strongly on how the credits for crops in rotation and for the soymeal co-product are calculated.

Biodiesel presents a scale-up problem both in terms of requirements for land area and fertilisers and in allocation of the inputs to co-products. So far, feedstock availability has not yet been a real barrier to soy biodiesel development. However, pressure for land-use change should be reduced. A genuinely sustainable biodiesel industry requires that the risks of indirect effects are significantly reduced by setting lower targets, by ensuring that feedstock production takes place on idle or marginal lands (*i.e.* lands of low competition), and/or by encouraging technologies that utilise non-edible crop based feedstock (such as algae or waste). Allocations applied for small-scale production (as assumed in most LCAs), where the by-products can replace other similar products, do almost certainly not apply on a very large scale. The glycerine market is already heavily oversupplied worldwide and more extensive biodiesel production is expected to lead to an even lower glycerine market value. Sustainable long-term production of soy biodiesel requires complementary socio-economic assessment. Socio-economic consequences of a global large-scale expansion of biomass use for energy are still obscure [240]. Future studies should not assess the prospects for (soy) biodiesel in isolation, but instead adopt a broader approach where several land-use mitigation options are considered as well as socio-economic goals. Large-scale biodiesel is not an ultimate alternative to fossil fuel.

Modelling of the agricultural phase is still far from satisfactory as the impact of previous crop management, the effect of the application of fertilisers on yield, the influence of soybean inoculation on N_2O emission, and the relation between tillage method and fertiliser use all need further evaluation. Data on oilcrop methods and agricultural practices should be harmonised, georeferenced and officially validated. Carbon emissions from deforestation will better be accounted for when new data become available. Modelling of the biodiesel pathway will benefit from better accounting for land-use changes also in interaction with market price evolution. Future LCA models should pay more

attention to crops succession, in particular to allocation and the effects of tillage, fertilisers and pesticides. More efforts are needed to harmonise LCA methodology for biodiesel impact assessment in order to allow better comparison between various biofuel pathways.

The latest EU proposal indicates that conventional biodiesel will not grow in energy volume beyond the 2011 level [216]. Developments of sustainability criteria, primarily involving factoring in the ILUC effect, will further cut back first-generation biofuels. The new area calculation methodology restricts the contribution of soy biodiesel. The EU proposal confirms that the future of biodiesel lies in the use for non-edible (advanced) energy crops with high crop productivity, grown on degraded land or requiring no land use. The availability of these feedstocks is still limited. Only biofuels with a low estimated risk of negative indirect sustainability effects and high overall GHG savings will be supported as part of the post-2020 renewable energy policy framework of the EU. Actually, there are few areas where biofuels are an acceptable use of biomass given more favourable alternative uses (food, feed, chemical products). Use of biomass for bio-based chemicals is more efficient (100% use) than as biofuels (at most 40% efficiency).

Soybean is not the most efficient feedstock for biodiesel because it occupies large tracts of land, incurs considerable carbon debt (in particular when considering ILUC), and has a low annual rate of saved carbon from replacing fossil diesel. In this respect both rape and oil palm biodiesel are better alternatives than soy biodiesel. Moreover, preference is to be given to the use of biomass feedstocks that do not have a high economic value for other uses than biofuels. Clearly, soybeans do not qualify.

Biodiesel is most valid when sourced and used locally. Intercontinental transport (USA-EU) is responsible for a high GHG impact (21% of total), *cf.* Section 5.3. Soy biodiesel – if produced sustainably – is a useful product for Argentina and Brazil to offset diesel imports for their developing domestic markets, is already a less obvious commodity for the US fuel market – mostly gasoline oriented –, is unlikely to make inroads in China – in need of soybeans and soy oil for food – and is not a most obvious product for the highly regulated European market (in terms of environmental requirements) and limited market prospectives for the future. Soy biodiesel production in Europe is not a winning idea. In a non-expanding EU market for conventional biofuels soy biodiesel (with low crop productivity, high IV, low GHG savings, high ILUC risk, anti-dumping duties, and need for sustainability certification) is also no longer an attractive import product. On the other hand, also Europe's export of the environmental impacts of bioenergy production elsewhere is not sustainable. The prospects for conventional biodiesel development in Europe are limited by the dearth of dedicated farming land and the trends in global demand. The EU market volume for conventional biofuels is likely to be reduced in the long term. The global biodiesel plant capacity might require further downward adjustment. The use of lignocellulosic biomass and algae will lead to environmental benefits and relieve the pressure on farming land. However, a recent report by the US National Academy of Sciences has raised concerns regarding the viability of algal biofuels at current technologies [241].

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